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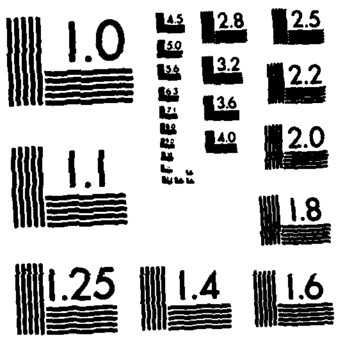

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The kinematic parameters of divergence and vorticity in the lowest 450 m of the atmosphere were calculated for a 750 km area in east central Illinois from wind measurements obtained using pilot balloons. The area for which the analysis has been made is triangular, west of Champaign/Urbana. These and similar data for the surface have been analyzed for nine days of the summer of 1979. Most of the observations were made during the afternoon and early evening hours during periods when tropical air masses overlay the observational network. The maximum surface →

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ABSTRACT (cont.)

temperatures on these days ranged from 26.5 to 35 C, and the surface dew-point temperatures varied from 18 to 24 C, approximately normal for temperature but more humid then normal. (The average dew-point for central Illinois is 18 C during July, 17 C in August.) The precipitable water content from the surface to 400 mb ranged from 3.2 to 5.3 cm, higher (by as much as 77% at the extreme) than the normal precipitable water over central Illinois during July or August (Lott, 1976).

State Water Survey Division
METEOROLOGY SECTION
AT THE
UNIVERSITY OF ILLINOIS

Illinois Department of
Energy and Natural Resources

SWS Contract Report 328

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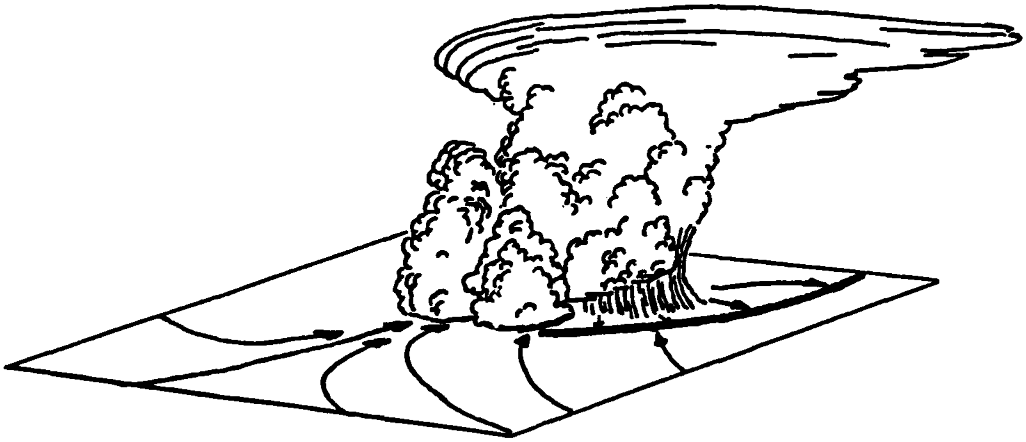

Technical Report 8
NSF Grant ATM 78-08865
Low Level Convergence and the
Prediction of Convection Precipitation

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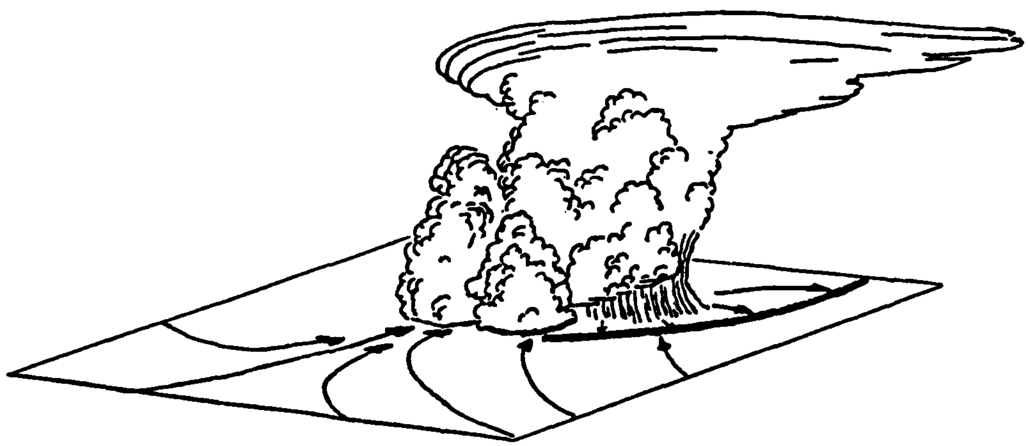

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Champaign, Illinois
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The project "Low-level Convergence and the Prediction of Convective Precipitation" is a coordinated research effort by the State Water Survey Division of the Department of Energy and Natural Resources, the Office of Weather Research and Modification in the National Oceanic and Atmospheric Administration, and the Department of Environmental Sciences of the University of Virginia. Support of this research has been provided to the State Water Survey by the Division of Atmospheric Sciences, National Science Foundation, through grant ATM-78-08865. This award includes funds from the Army Research Office and the Air Force Office of Scientific Research of the Department of Defense.

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SECTION I

INTRODUCTION

Byers and Braham (1949), reported on observations showing the relationship between surface and mid-level convergence and convective activity. Their measurements indicated that convergence occurred in the surface mesoscale wind fields for 20 to 30 minutes prior to the first appearance of a radar echo associated with thunderstorm formation. Likewise, convergence was found in the mid-level winds around forming cumuli. Using Florida data with similar resolution, Ulanski and Garstang (1978) found a typical "signature" in the temporal evolution of surface divergence which could be related to the rainfall volume and maximum rainfall rate of individual convective elements. This signature was associated with the thunderstorm gust front and they hypothesized that such a signature could be used to predict the onset and intensity of convective precipitation.

One of the objectives of the VIN* project was to further test the Ulanski-Garstang hypothesis for Florida and to examine its applicability to the Midwest. In addition, the relationship between the surface and sub-cloud layer wind parameters was to be examined to deermine the depth through which the surface kinematic fields might be representative. It was perceived that the link between the surface and the cloud layer might be strongest in the sub-cloud region, and that the mesoscale process might be reflected in the sub-cloud region even more strongly than at the surface. To explore this possibility, a small pilot balloon network was implemented as part of the observational program carried out in Illinois in 1979 (Ackerman et al., 1983).

This report focuses on the sub-cloud layer (200 to 700 m MSL) wind field and its relationship to surface convergence and rainfall within a dense mesoscale network on nine days during the field program. In Section II, the sub-cloud layer kinematics are presented for each day and the synoptic and mesoscale weather is briefly described, to provide background for the discussion. The final section provides a summary, synthesization and discussion of the study results.

*VIN is formed from the names of the cooperating organizations: University of Virginia, Illinois State Water Survey, and NOAA.

Background

Using surface wind data from the NOAA/FACE, Watson et al. (1981) concluded that areal divergence (inflow) held promise for predicting the initiation, amount, and maximum intensity of rain within an area on the Florida peninsula. In addition, the "weighted" convergence, (the average convergence over the region of converging flow only), was found to be a better predictor of rain than the total areal divergence. Watson and Holle (1982) conducted a similar analysis using surface data collected in central Illinois during the VIN field experiment. They found a correlation between the surface inflow and rainfall in Illinois of 0.5, compared to 0.6 in Florida. Similar to the Florida results, the correlation between mass inflow and rainfall was improved when synoptic parameters, such as relative humidity, stability indices, and wind speed between 300 and 3,000 m were used to stratify the data.

Achtemeier (1980), using rainfall and wind data collected in METROMEX in 1975, examined the divergence patterns within a small network similar to that of Ulanski and Garstang (1978). Based on 19 "raincells" from a 7-day sample, he found that the agreement between rainfall and the spatial distribution of divergence remained small until approximately 15 minutes prior to the start of rain within the network. He also concluded from case studies that there was a physical relation between rainfall and surface convergence at both the raincell- and network-scales.

Data Base and Analysis Techniques

The special mesoscale networks in VIN consisted of a dense raingage network (station spacing about 4.8 km) and a slightly smaller and less dense network (station spacing about 6.5 to 10 km) of instruments to measure temperature, humidity, pressure, and wind (Figs. 1 and 2). The networks were located in east central Illinois (see state map lower right, Fig. 1). A radiosonde site at which releases were made at 1300 and 1800 CDT on operational days was co-located with the CHILL radar near the eastern boundary of the raingage network. In addition, special radiosonde observations were made at 1300 CDT by the National Weather Service (NWS) stations at Peoria, IL and Salem, IL, on request.

The winds in the lower troposphere were measured at three single-theodolite observational sites. These 3 stations formed a triangle with area of 750 km^2 in the center of the VIN network (Fig. 2). Pibal (pilot balloon) releases were made every 30 minutes, usually from early afternoon to dusk, using 30-g balloons. The azimuth and elevation angles were measured every 30 seconds. Winds were calculated for 30-second layers (approximately 100 m) using standard techniques. The balloon height at the end of every 30-second interval was calculated using the

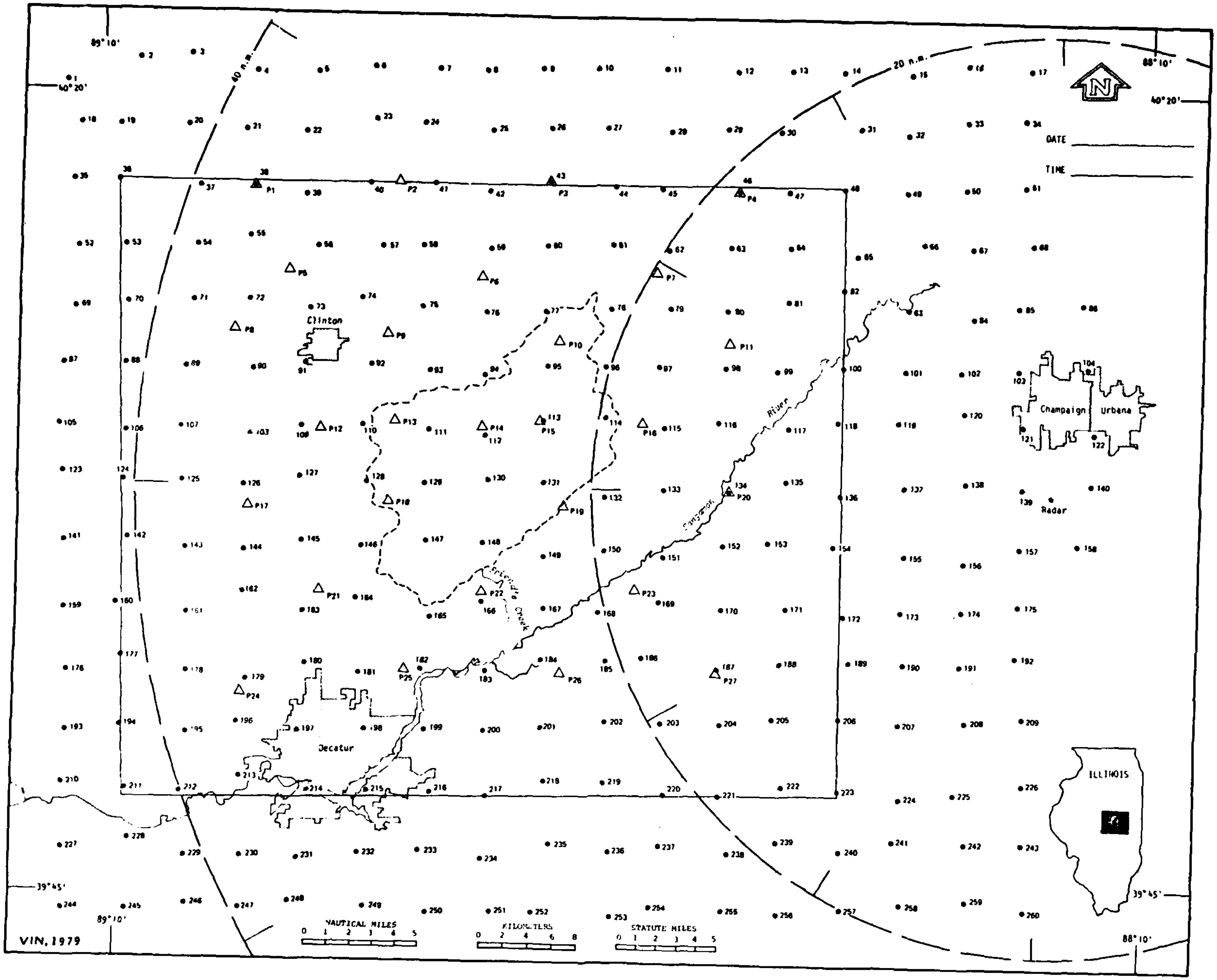


Figure 1. VIN 1979 dense raingage network. Inner rectangle delineates dense wind network; arcs indicate distance from radar.

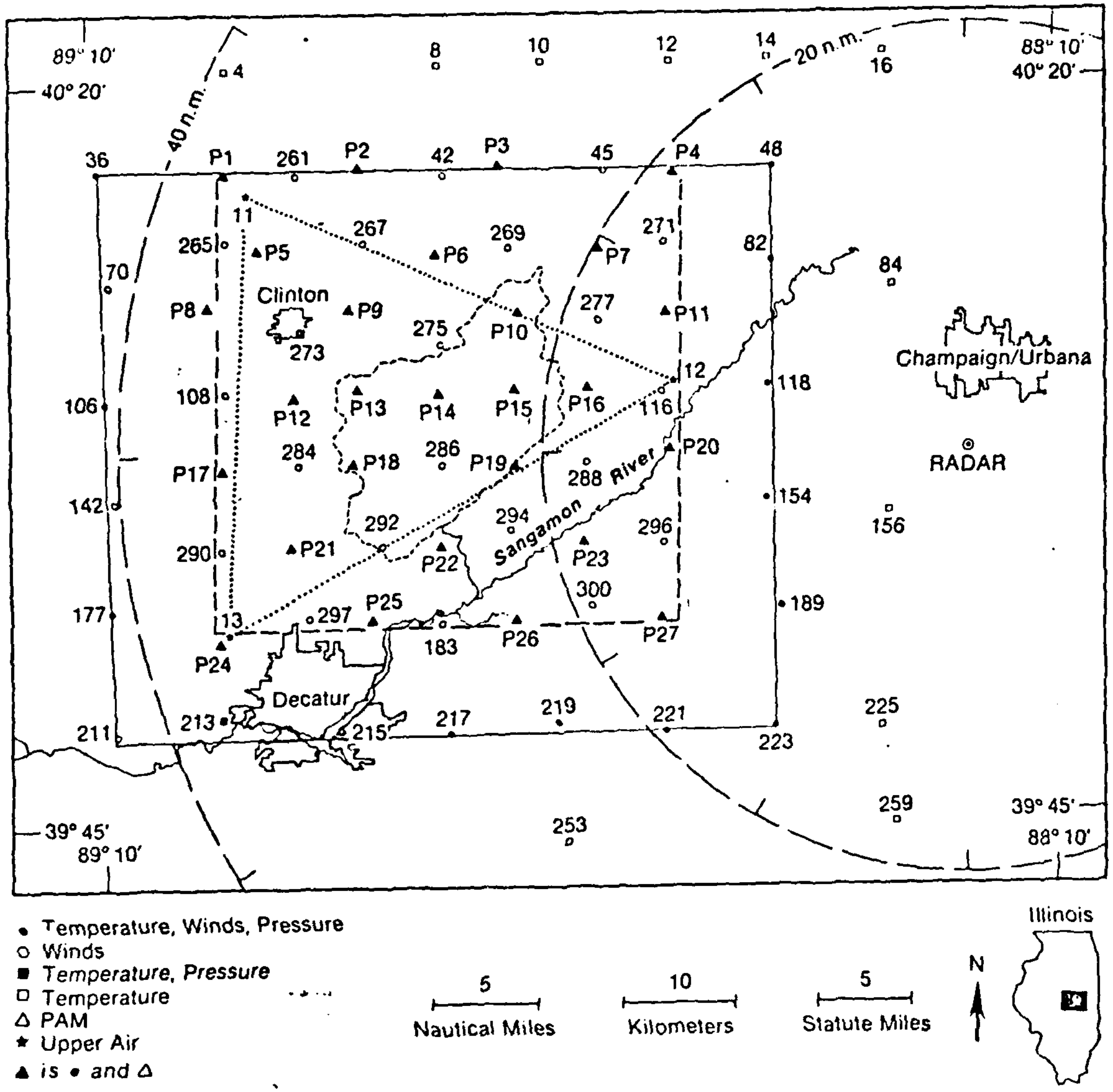


Figure 2. VIN 1979 wind network. The dashed line encloses the inner network, the solid line shows the outer network boundary, and the dotted line, the pibal area.

standard rise rates for 30-g balloons. Divergence and vorticity were calculated at intervals of 50 m MSL for the triangle by the areal "expansion" method (Bellamy, 1949), using winds interpolated from the calculated winds at each station. The vertical velocity was then calculated from the continuity equation. These calculations were averaged over 100-m MSL overlapping layers to determine the smoothed values of divergence, vorticity, and vertical velocity at 50-m MSL intervals.

The study reported on herein was limited to the layer that extended from the surface (about 275 m MSL) to 700 m MSL. This provided the most complete data base for the nine days and a consistent means of comparison. Surface divergence, calculated from the measurements at three surface stations which closely approximated the upper-air triangle, were supplied by Watson, one of th NOAA participants in VIN (1981, private communication). Tota rainfall amounts and percent of area covered by rain during 30 minute periods were obtained from recording raingages in the tri angle formed by the pibal stations and in "downstorm" areas whic were delineated by displacement of triangle limits by distanc equal to 1-hour storm movement. There were 29 raingage station in the pibal triangle; the number of stations in downstorm areas varied.

SECTION II

DAILY ANALYSES

Day-to-day descriptions of the sub-cloud layer winds and derived kinematic parameters, surface divergence, and rainfall for the pibal triangle are given below for each of the nine days examined in this study. In addition brief background information about the synoptic and mesoscale weather is provided.

A uniform approach was used in the analysis and in the reporting of the results. The routine NWS surface and upper air analysis were closely examined for dynamic factors which could trigger convection, but no special computations were made. Thermodynamic indices were calculated for the State of Illinois from both routine and special radiosondes. The indices computed were Showalter Index, Lifted Index and the precipitable water for the layer from the surface to 400 mb.

The surface wind and raingage data were continuously available at 5-min intervals throughout the 24 hours. As mentioned in Section I, the boundary layer measurements were available only at 30-min intervals and for several hours during the afternoon and early evening, with a 30-min break midway through the observational period set aside for a rest period for the single observer at the site.

The discussion for each day centers around three diagrams. One is a single panel, height-time section of wind direction and speed, from one of the three stations having the most complete data set for the day. The second figure has three panels, giving height-time cross-sections for the pibal triangle of (a) divergence, surface to 700 m MSL, (b) vertical velocity obtained by integrating the continuity equation from the surface upward, and (c) vorticity from 300 to 700 m MSL. Since the computations of the kinematic parameters require measurements from all three sites, none of the three parameters could be determined when observations were missed because of rain or because the balloon was obscured at one or more stations. When the analysis was based on interpolated information through these periods of missed data the isolines are shown by dashes.

The third figure used in the discussion is also 3-panel and is usually presented first because reference is made to it throughout. In the top panel (a) are given a time series of the column-average values of divergence for the layer surface to 700 m MSL, column average vorticity for the layer, 300 to 700 m MSL, and the vertical motion calculated at 700 m MSL. In the middle panel, (b), is plotted the time series of the average surface divergence in the triangle for each 5 minutes. In the bottom panel, (c), are shown the time series of the total 30-min rainfall in the triangle and of the fraction of raingages in the triangle in which rain was recorded during the 30-min period.

13 July 1979

Central Illinois was embedded in a warm, tropical air mass throughout 13 July. The remnants of Hurricane Bob which had moved up the Mississippi Valley from the Gulf in the previous 48 hours had reached southern Ohio by 1300 CDT. A slow-moving cold front stretched from northern Wisconsin to northwest Kansas during the afternoon and evening. The upper-tropospheric trough associated with Hurricane Bob filled during the day, and the upper-air flow became zonal by evening with a shallow short wave moving across the northern part of the United States.

The afternoon maximum temperatures ranged from 31 to 34 C, and the surface dew-point temperatures were 18 to 23 C. The precipitable water, surface to 400 mb, at 1300 CDT varied from 3.4 cm at Salem to 4.1 cm at Peoria, and the Lifted and Showalter stability indices ranged from -2 at Peoria to -3 at Salem. Thus, the atmosphere was conditionally unstable over Illinois.

Showers and thunderstorms formed over northwestern Illinois in advance of the cold front and spread southeast into central Illinois. Additional convective activity was initiated in advance of this area of showers and thunderstorms. Convective echoes formed within the VIN network at 1435 CDT and continued until 1935 CDT. The more intense convective activity on this day was south of the network. The heaviest rains within the network fell between 1500 and 1700 CDT, as individual convective elements moved from the west-northwest at 40 to 55 km/hr.

Within the pibal triangle rains fell from 1505 to 1725 CDT and again from 1855 to 1905 CDT (Fig. 3c). The first rains in the triangle were light scattered showers in advance of the main line of showers and thunderstorms which advected into the triangle at 1540 CDT. The most intense rains during the first rain period fell southwest and south of the triangle. The second period of rain in the triangle was very short and light (less than 1 mm accumulation), and consisted of a rainshower on the northern edge of the general storm area.

The winds in the low levels shifted from the south-southeast through west to north between 1430 and 1530 CDT (Fig. 4). The wind speeds during this period were light, generally less than 2.5 m/sec. The wind continued to change direction over the next two hours, in response to the rainshowers which formed in the triangle, and/or to the more intense convective activity which moved onto the northern portion of the dense raingage network at 1505 CDT. It shifted back to south and southwest when the first rain period in the triangle ended. The wind speed was generally less than 2 m s^{-1} before the rain, increased slightly after the first rain period, with larger increase after the main cloud line moved through the area. Whereas the wind direction was uniform through the lower 500 m early on, it veered with height after 1830 CDT.

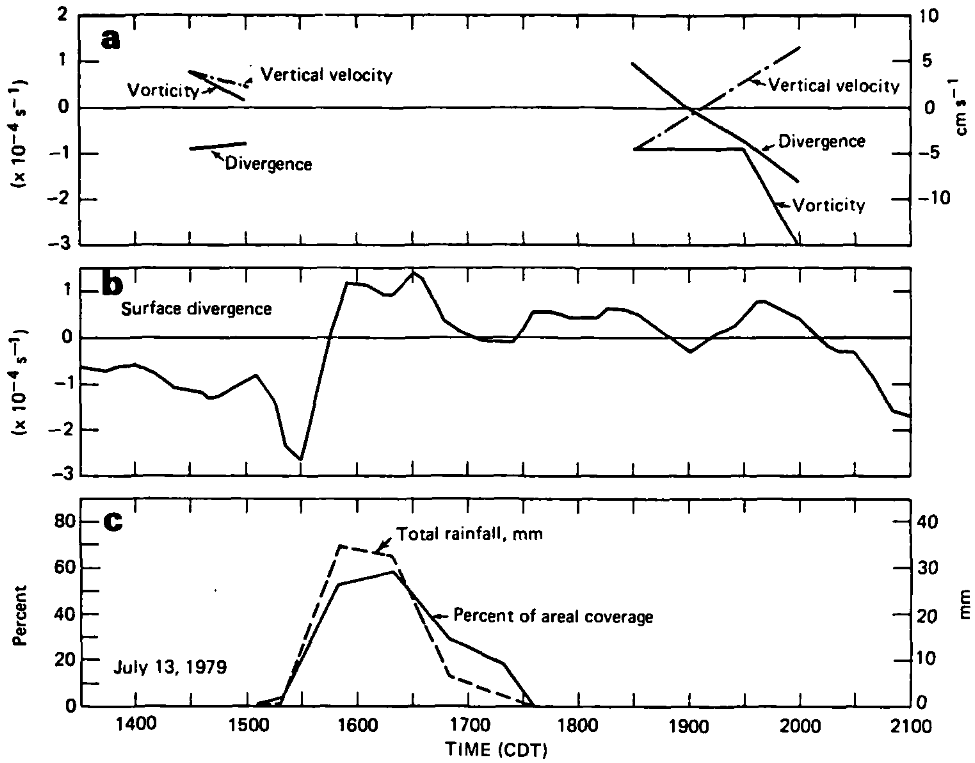


Figure 3. *Time series of (a) column-average (300-700 m MSL) divergence and vorticity (10^{-4} s^{-1}) and vertical motion at 700 m MSL (cm s^{-1}), (b) surface divergence and (c) total 30-min rainfall and percent of area covered, all for pibal triangle, on 13 July 1979.*

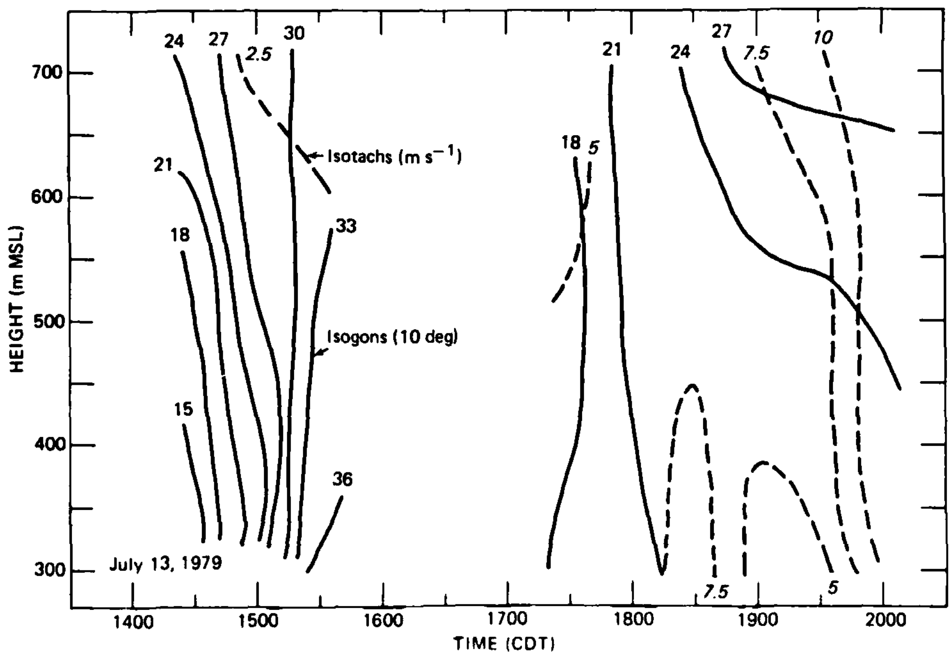


Figure 4. *Time-height analyses of wind direction (isogons) and wind speed (isotachs) in sub-cloud layer on 13 July 1979.*

Winds were available at all three sites at 1430 and 1500 CDT and again from 1830 to 2000 CDT. Rain occurred at one or more sites at observation times between 1500 and 1730 CDT. In the half-hour prior to the start of rain (1430-1500) the layer from the surface to 700 m MSL was convergent (Fig. 5a). The average convergence for the layer decreased between 1430 and 1500 CDT from -0.9 to -0.7 x 10^{-4} sec^{-1} (Fig. 3a); however, the average convergence for the lowest 200 m from the surface to 450 m MSL, increased from -0.6 to -1.4 x 10^{-4} sec^{-1}. After the first rain system moved out of the triangle, the wind field was divergent with a mid-level maximum (1830 CDT). Subsequently, the divergence decreased and the wind field became increasingly convergent and convergence characterized the wind field above the surface after 1930 CDT, increasing in magnitude with height. The effect is especially evident in the vertical velocity (Fig. 3a), as it changed from subsiding motion of 4.2 cm/sec at 700 m MSL at 1830 CDT to an upward motion of 6.7 cm/sec by 2000 CDT.

The relative vorticity was mostly cyclonic prior to the start of rain at 1505 CDT (Fig. 5ac, 3a). After the first rain it was weakly anticyclonic but increased rapidly after the main shower line had passed through (1930 to 2000 CDT).

The surface flow in the triangle was convergent prior to the start of the rain (Fig. 3b), as it had been from about 0700 CDT. There was a gradual increase in surface convergence from approximately 1400 to 1445 CDT, followed by a decrease, and then a rapid increase in convergence from 1505 CDT to 1530 CDT, signaling the beginning of the shower outflow with its typical "S-shaped" signature. This "signature" began at the same time that the rain started in the triangle (1505 CDT). Concurrently there was a line of showers and thunderstorms NW of the triangle. The large changes in surface divergence after 1505 CDT were in response to the outflow asociated with the convection within and/or outside of the triangle. The increase in convergence from 1400 to 1445 CDT was the fore-runner of the subsequent rain storm.

The surface flow changed from divergent to convergent and then back to divergent between 1820 and 1940 CDT. These changes in the surface field appears to have been related to the widely scattered light showers which fell in the raingage network between 1855 and 1935 CDT, one of which skirted the pibal triangle.

The average boundary layer measurements showed both convergence and cyclonic vorticity in the triangle from 1430 to 1500 CDT, prior to the start of rain in the triangle (Fig. 3a). At 1830 CDT, after the main rains in the triangle, the flow was anticyclonic and divergent. Although the sub-cloud layer wind field was convergent by 1900 CDT, with convergence increasing in magnitude over the next hour, as the flow in the triangle became increasingly more anticyclonic. The surface divergence values also began to decrease and become convergent, but only after 2010 CDT, lagging the boundary layer convergence by about 1 hour.

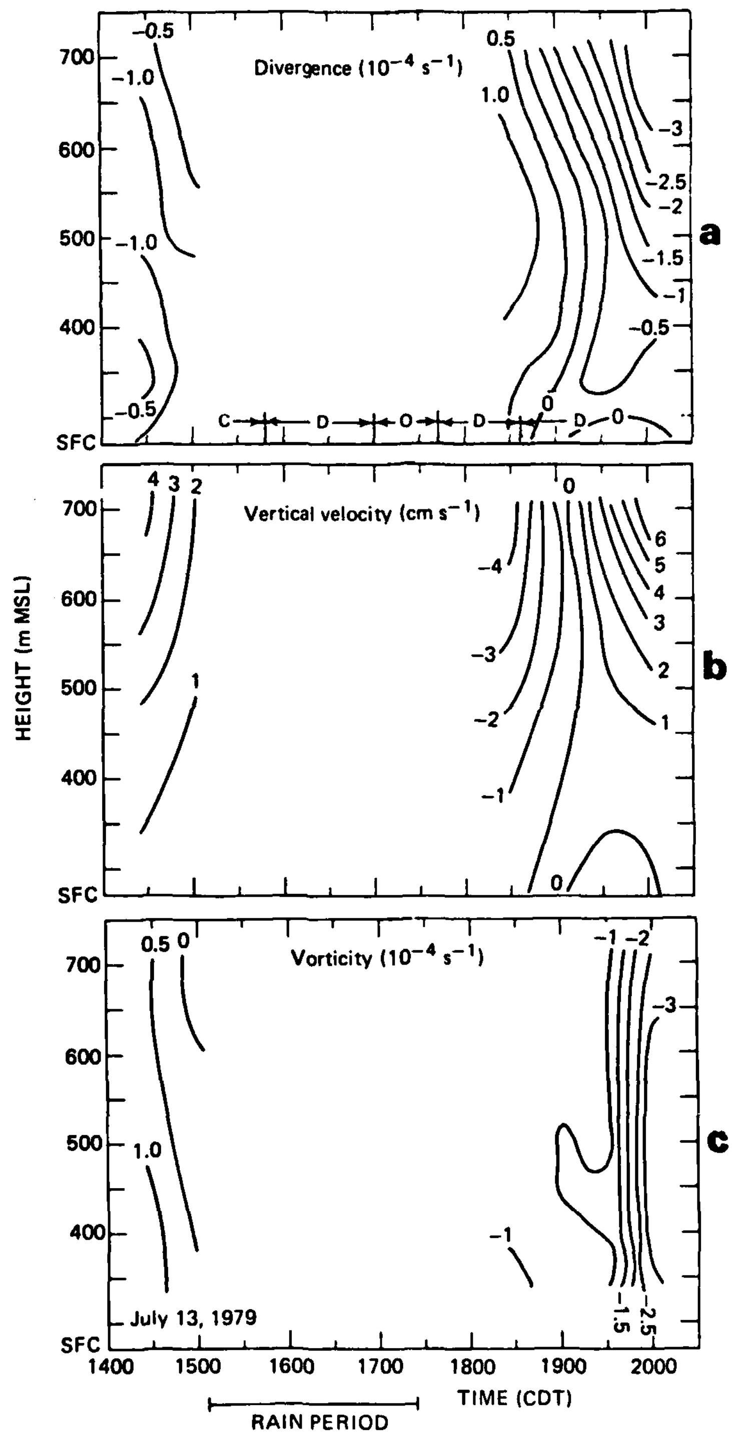


Figure 5. *Time-height analyses of (a) divergence, (b) vertical motion, and (c) vorticity, in the sub-cloud layer on 13 July 1979. Times of surface convergence/divergence when pibal data are missing is indicated by C/D, resp. in (a).*

14 July 1979

A cold front extended southwestward from the northeast corner of Illinois to the northeast corner of Missouri at 1300 CDT on 14 July. A short wave, which was well defined at 850 and 700 mb, was situated over Iowa and Kansas at 0700 CDT. Both these features moved rapidly across Illinois during the afternoon and evening, with the front passing through the VIN network in central Illinois between 1830 and 1900 CDT. By 2200 CDT the front had traversed all but the southern tip of Illinois. Satellite photo's showed the southern half of Illinois mostly cloud free during the morning and early afternoon.

Showers and thunderstorms formed over most of the southern two-thirds of Illinois by 1500 CDT. These scattered showers and thunderstorms continued to 1700 CDT, when the convective activity became organized into N-S lines. Two lines, one lying to the south and the other to the north of the VIN area, skirted the raingage network. Light rain occurred at one station in the pibal triangle (Fig. 6c). The strongest convection (according to NWS WSR-57 radar network) in Illinois in the late afternoon and evening occurred in the south, over 130 km south of the VIN network.

The surface dew-point temperatures in the tropical air mass ahead of the cold front ranged from 21 to 24 C. The 1300 CDT Champaign sounding indicated 5.3 cm of precipitable water in the column from the surface to 400 mb, and the Lifted Index was -2. Thus, the atmosphere was moist and conditionally unstable, and able to support organized convective activity providing suitable dynamics existed.

The winds in the layer between 300 and 700 m MSL gradually shifted from 210 to 250^{o} between 1400 and 1830 CDT, as the cold front approached (Fig. 7). The winds veered more rapidly with the frontal passage between 1830 and 1900 CDT, coming around to northwest by 2000 CDT. The wind speeds above 500 m MSL varied from 7.5 to 13 m/sec, whereas the speeds below 500 m MSL were between 5 and 7.5 m/sec.

The wind field prior to the cold frontal passage was convergent near the surface except for the period from 1630 to 1730 CDT (Fig. 6b), but divergence dominated the upper portions of the sub-cloud layer from 1500 to 1800 CDT (Fig. 8a). Just prior to the cold frontal passage (1830 to 1900 CDT) the flow became convergent throughout the sub-cloud layer, resulting in upward motion of over 6 cm/sec at 700 m MSL (Fig. 8b). Immediately after the cold frontal passage the wind field became divergent and the vertical motion quickly reversed. From 1500 on, the sign of the divergence at the surface was the same as in the layers above, but maxima tended to occur aloft.

The vorticity was anticyclonic until 1530 CDT throughout the sub-cloud layer, then it became cyclonic in the upper levels (>500 m MSL) and remained so until 1930 CDT (Fig. 8c). Below 500 m MSL the relative vorticity alternated between cyclonic and

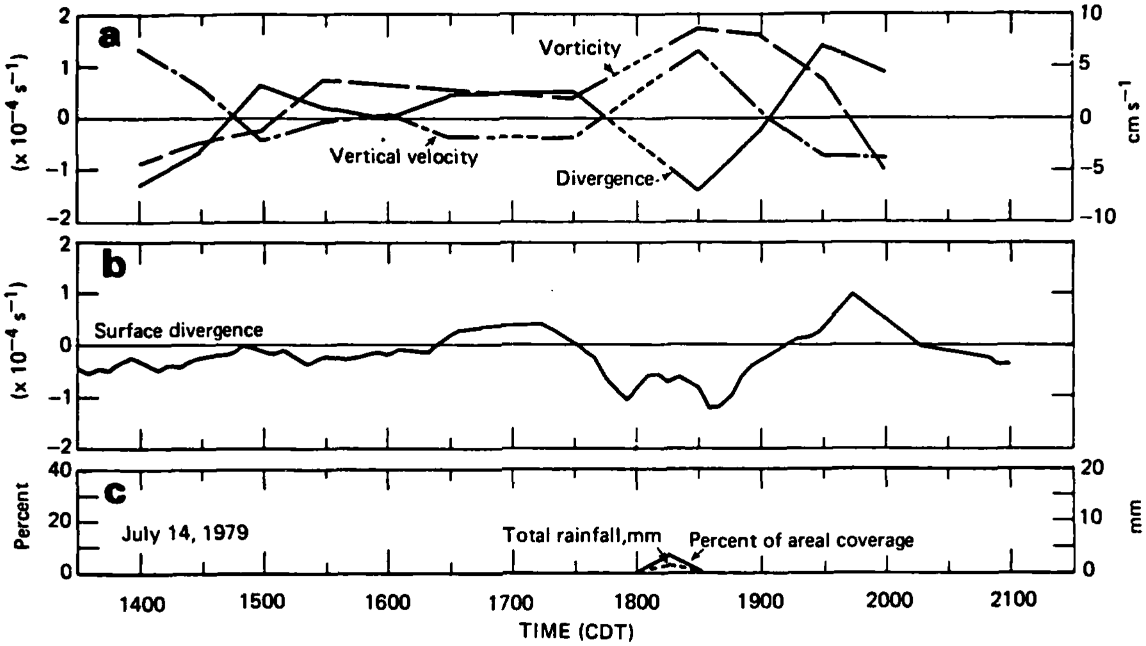


Figure 6. Same as Figure 3, for 14 July 1979.

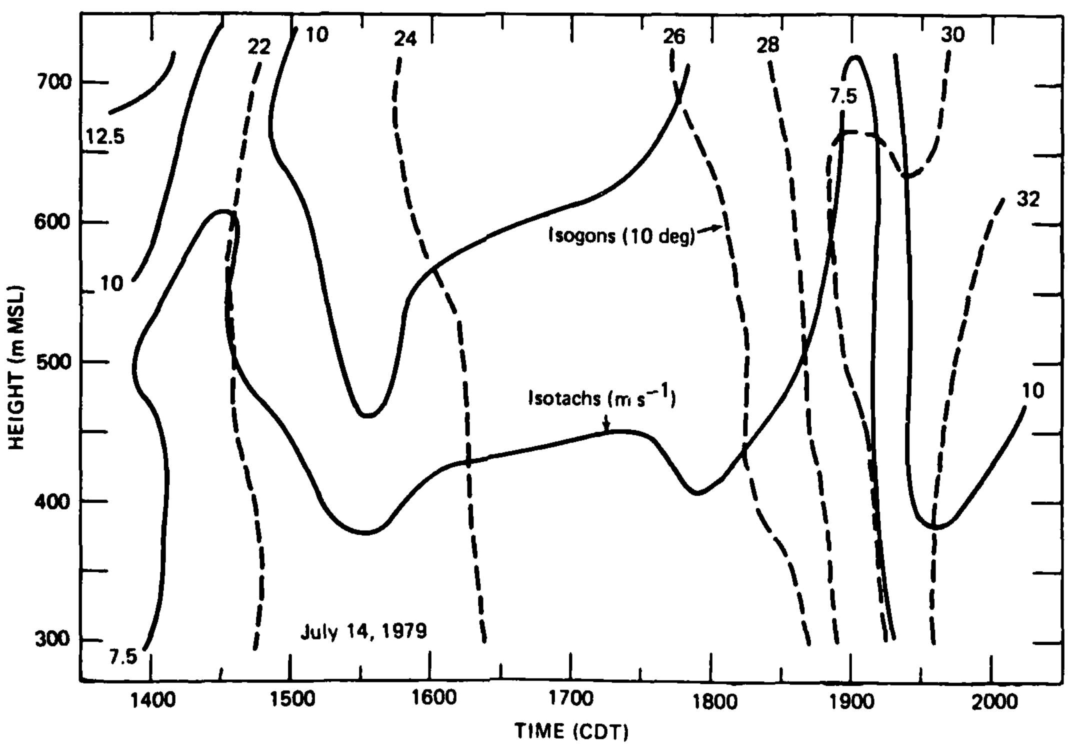


Figure 7. Same as Figure 4, for 14 July 1979.

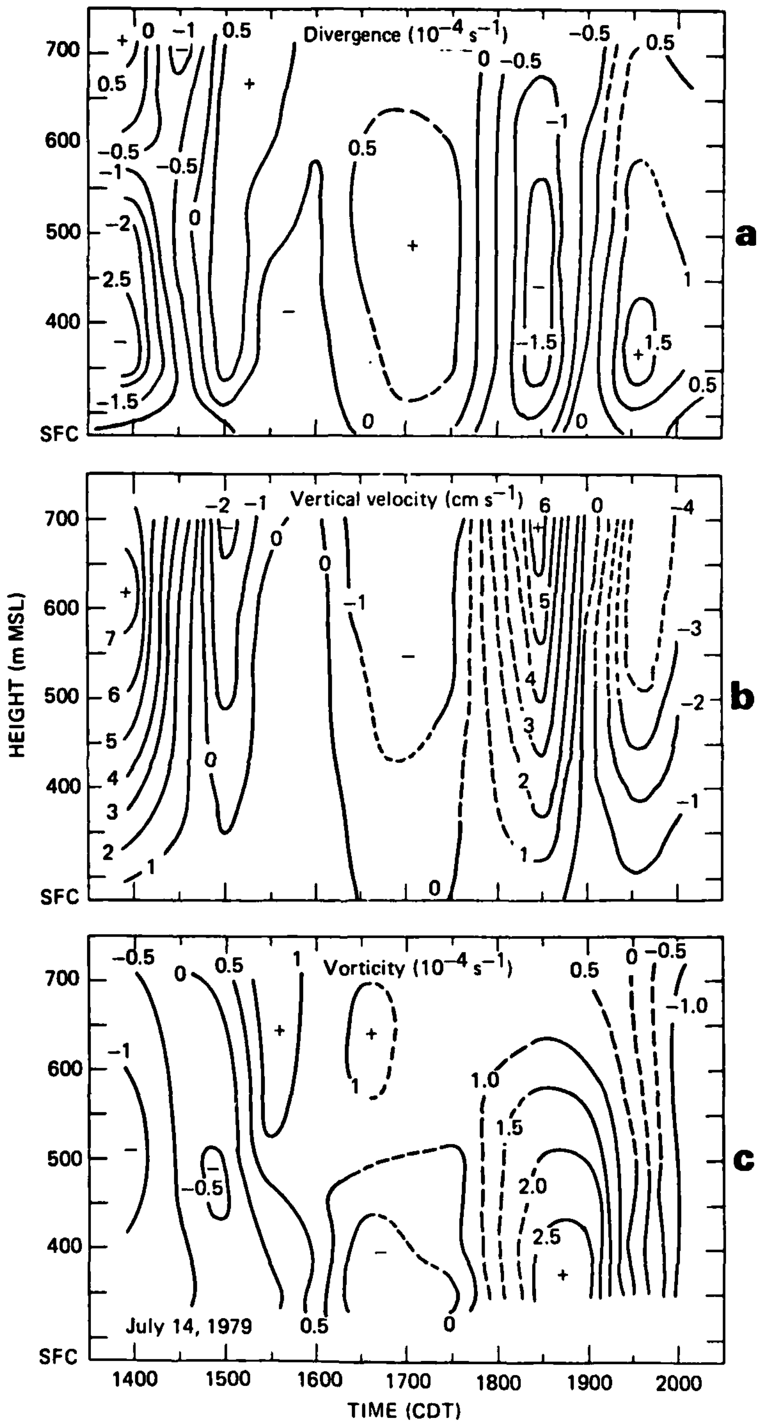


Figure 8. Time-height analyses of (a) divergence, (b) vertical motion, and (c) vorticity in the sub-cloud layer on 14 July 1979.

anticyclonic until 1730 CDT, about an hour prior to the frontal passage, when it became cyclonic and remained so until 1930 CDT. After the frontal passage, the vorticity shifted to anticyclonic again throughout the layer.

Only one short shower of 0.6 mm fell within the triangle (one station) during the afternoon and evening of 14 July. There was strong surge in surface convergence from 1730 to 1755 CDT, just prior to the rain within the triangle when it increased from near zero at 1730 CDT to 1.1 x 10^{-4} sec^{-1} at 1755 CDT (Fig. 6b).

Other rain showers occurred along the southern and northern edges of the VIN raingage network, but no others in the triangle. The rains along the southern edge began at 1615 CDT and lasted until 1735 CDT. These rains, generally light with a maximum gage rainfall of 5.5 mm, moved east. Rains advected east along the northern edge of the triangle beginning at 1720 CDT and lasting until 1900 CDT. These showers built on the southwest flank of the larger area of convection, and it was the southern edge of one of these storms that grazed the triangle. The heaviest gage rainfall observed along the northern border of the VIN network was 5.5 mm.

It is possible that the surge of convergence at the surface between 1730 and 1755 was due to outflow from one of these convective systems or it could have been associated with the frontal passage. The second surge of convergence, between 1820 and 1840 CDT, however appears to be associated with the frontal passage. The peak in divergence at 1945 CDT does not appear to have been caused by rain on the network, but could have been associated with the dynamics of the frontal passage or with outflow from a distant convective system.

The average flow for the column from 350 to 700 m MSL after 1500 CDT was characterized by cyclonic vorticity, with maximum just prior to and during frontal passage. The strong divergence noted over the triangle at 1400 CDT was associated with anticyclonic flow, whereas the convergent wind field at 1830 CDT was associated with cyclonic flow in the sub-cloud layer.

24 July 1979

Central Illinois was embedded in a broad area of southerly flow from the Gulf of Mexico throughout the afternoon and evening hours of 24 July. Showers and thunderstorms formed in the moist, tropical air mass in the area most of the day. A dynamic "trigger" was provided for the storms by a nearly stationary upper-air trough situated over central Missouri and Iowa. Hurricane Claudette moved onto the southeast Gulf Coast of Texas during the day, and a cold front which stretched from northwest Wisconsin to the Panhandle of Texas moved very slowly east. This front remained well west of Illinois.

The afternoon high temperatures in Illinois ranged from 27 to 32 C, and the dew-point temperatures were 21 to 23 C. At 1300 CDT the precipitable water from the surface to 400 mb ranged from 4.5 cm at Champaign to 5.2 at Salem. All three special soundings at 1300 CDT (Champaign, Peoria, and Salem) had Lifted Indices of about -2, which indicated that the atmosphere was thermodynamically favorable for convection.

Within the pibal triangle there were periods of rain in the afternoon and evening, a showery period from 1550 to 1625 CDT and continuously from 1715 to beyond 2000 CDT (Fig. 9c). Rains were observed over some part of the VIN raingage network throughout the day on 24 July and continued into the morning of the 25th. The rain activity during the afternoon and evening came from small radar echoes over the network and from a series of lines oriented southwest-northeast. The individual elements moved from the southwest and west. At least one of the thunderstorm lines developed within the network.

Pibals were released every 30 minutes from all three sites from 1330 to 1800 CDT except at 1530. The winds were generally from 180 to 190° within the sub-cloud layer from early afternoon to 1800 CDT (Fig. 10). Wind speeds were generally less than 10 m/s except for a slightly higher values in the upper part of the layer after 1700 CDT. This wind maximum occurred approximately 30 minutes after the onset of the second period of rain within the triangle.

The time-height section of the sub-cloud layer divergence (Fig. 11a) indicates a rapid change from convergence to divergence and then back to convergence between 1330 and 1500 CDT. The divergence values at 500 m MSL changed from -0.9 to +1.3 x 10^{-4} sec^{-1} between 1330 and 1400 CDT, and then back to -0.1 x 10^{-4} sec^{-1} at 1430 CDT. Throughout this change in the sub-cloud divergence, the surface flow remained weakly convergent. There was no tendency for the surface pattern to become divergent, in fact the general tendency of the surface pattern was to become more convergent between 1305 and 1415 CDT (Fig. 9b). From 1500 to 1700 CDT the flow in the triangle was convergent from the surface to 700 m MSL, with the maximum convergence in the upper levels. After 1700 CDT the flow became divergent, and by 1800 CDT it reached a maximum of +2 x 10^{-4} sec^{-1} at 550 m MSL. The surface flow was divergent for a short time between 1730 and 1800 CDT, but became convergent again by 1800. Thus, the surface divergence did not always mirror that in the layer immediately above, even in sign.

The vertical velocity (Fig. 11b) near the surface was positive from 1305 CDT until 1725 CDT, but aloft there was a short period of subsidence at 1400. The upward motion in the sub-cloud layer maximized at 1600 CDT with a value of 7.4 cm/sec at 700 m MSL. Between 1630 and 1730 CDT the vertical motion reversed reaching an area-average downward value of -4.6 cm/sec at the top of the layer.

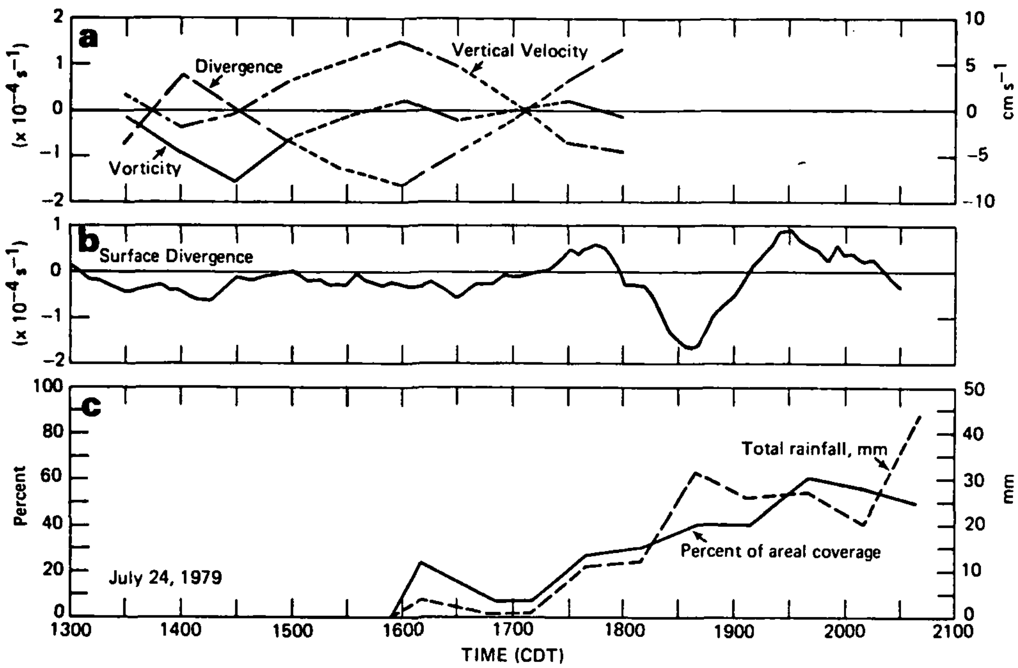


Figure 9. Same as Figure 3, but for 24 July 1979.

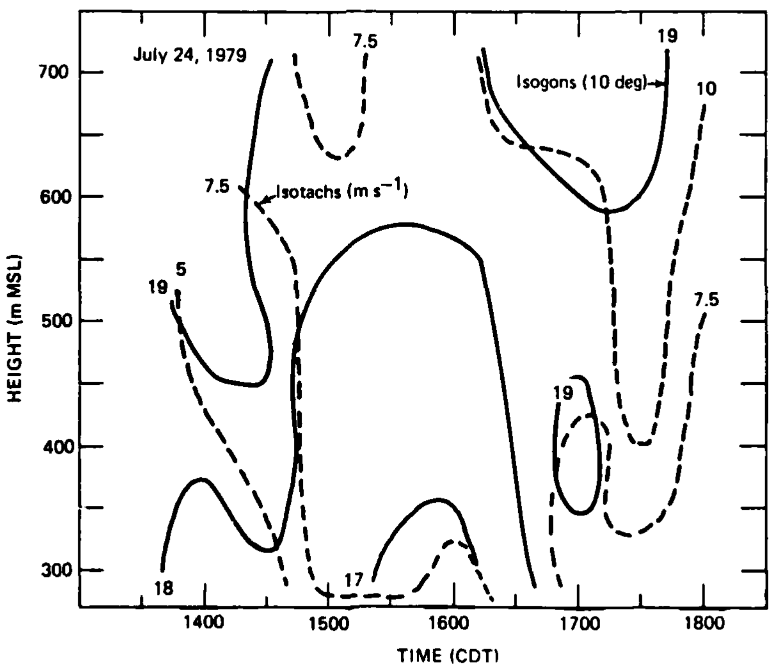


Figure 10. Same as Figure 4, but for 24 July 1979.

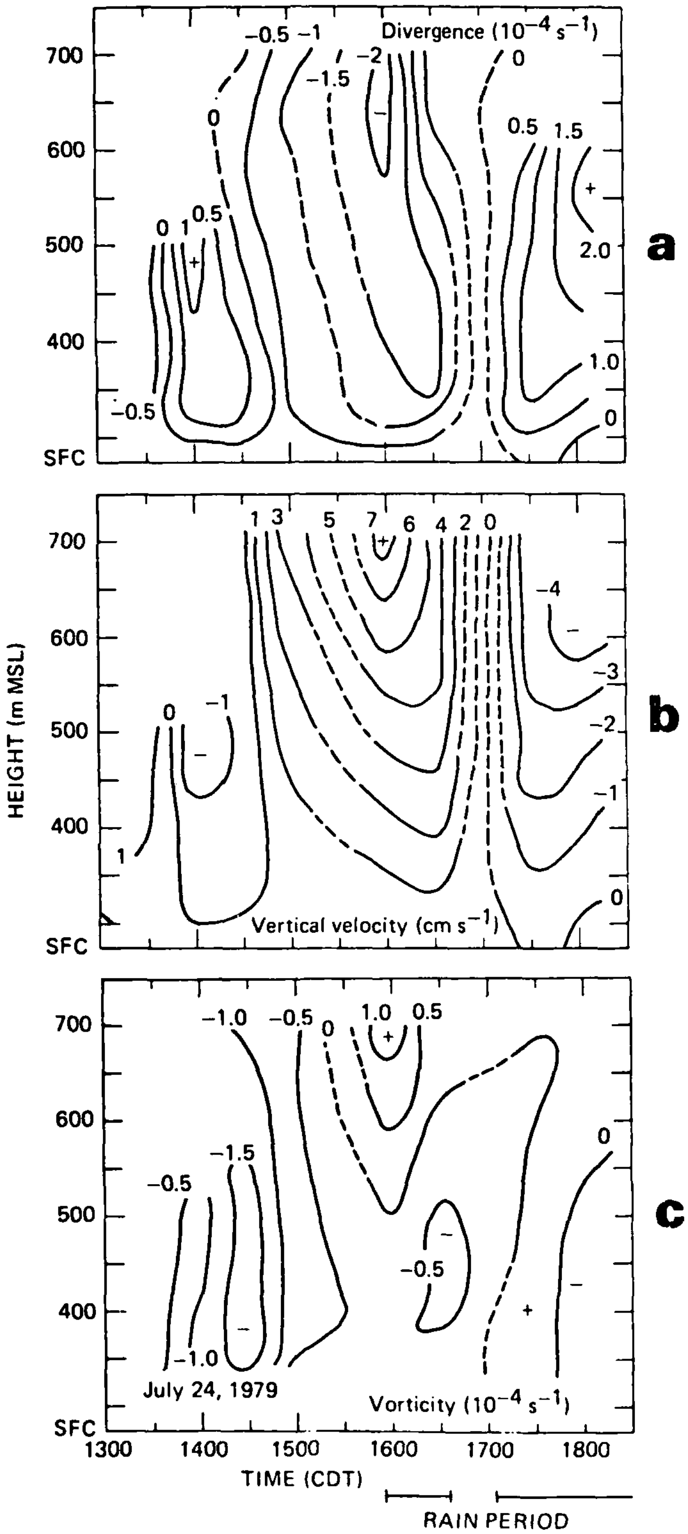


Figure 11. Same as Figure 8, but for 24 July 1979.

The sub-cloud layer vorticity was weakly anti-cyclonic during the afternoon, except for levels above 500 m MSL (Fig. 11c). From 1530 to 1800 CDT, the flow in the upper part of the layer had cyclonic vorticity, coincident with the strongest convergence and upward motion. The flow was cyclonic throughout the layer for a short period around 1700, just as the second rain period started.

The summary diagram of the surface and upper-air measurements (Fig. 9) shows that a long period of convergence preceded the main rains and that the greatest values of surface divergence and convergence occurred after 1700 CDT when it was raining in the triangle. These surface changes in divergence were probably in response to convection both within and outside the triangle, and it is difficult to relate the "signature" to any single convective complex. Prior to the onset of rain in the triangle the strongest surface convergence was -0.6×10^{-4} sec^{-1} at 1415 CDT. For the next two hours, it meandered between near zero and -0.4×10^{-4} sec^{-1}. At 1620 CDT, about the time that the first rain period within the triangle ended, the convergence at the surface increased from -0.3 to nearly -0.6×10^{-4} sec^{-1}, and then decreased relatively steady until 1720 CDT when the flow at the surface became divergent. The second period of rain in the triangle began at 1700 CDT, approximately 30 minutes after the doubling in surface convergence. The layer-average convergence and upward motion in the sub-cloud layer maximized at 1600 CDT, about 1 hour prior to the onset of the second rain period, and near the end of the early rains in the triangle.

The average sub-cloud flow was divergent at 1400 CDT while the surface field was convergent. After 1430 CDT the sub-cloud flow became convergent, increasingly so for 90 minutes thereafter. However, at the surface there was little or no change until 1620 CDT. The decrease in the layer-mean convergence from 1600 to 1800 CDT preceded that at the surface by about 30 minutes. On the other hand, there appears to have been little or no lag at the surface in the reversal from convergence to divergence shortly after 1700 and, though the data aloft end at 1800, there is a suggestion that the return to convergent flow at the surface preceded that in the 400 m above.

30 July 1979

Two cold fronts, one extending from Minnesota to Colorado and the other from northern Minnesota to North Dakota, moved slowly southeast during the day and evening of 30 July. However, this dual cold front system did not reach northern Illinois until the morning of 31 July. Short-wave troughs aloft and a strong jet at 200 mb accompanied the fronts providing favorable dynamic conditions for convection along and in advance of the cold front.

During the afternoon and early evening of 30 July, east-central Illinois was embedded in a warm, tropical air mass with

afternoon temperatures ranging from 30 to 34 C. At 1300 and 1900 CDT the precipitable water over southern Illinois was 4.8 and 4.7 cm, respectively, and the Lifted Index was -5 and -8, respectively, while at mid-day at Champaign the precipitable water was 3.9 cm. Thus, the air mass over southern and central Illinois was capable of supporting intense thunderstorm activity provided a dynamic mechanism was present.

There were two rain periods during the afternoon and early evening hours on 30 July. The first rain in the pibal triangle began at 1525 CDT and maximized between 1545 and 1615 CDT (Fig. 12c). This rain system moved east and merged with a mesoscale rain storm over and east of Champaign-Urbana (Changnon and Vogel, 1981). Although the system as a whole produced heavy rains to the east, the rain was quite light in the triangle. The second rain period was associated with a squall line which moved across the network from the north, with individual precipitation entities within the squall line moving from the west. This rainstorm moved onto the triangle at 1825 CDT, and passed through by 2030 CDT. The heaviest rains in the triangle fell from 1845 to 1945 CDT.

Pilot balloon measurements were made between 1330 CDT and 1800 CDT. The winds prior to and during the first rain period were from the SSW at 5 m/s near the surface to greater than 10 m/s above 400 m MSL (Fig. 13). After the first period of rain ended, the winds veered and were from the southwest (220 to 230^{o}) for a short period--and then shifted dramatically, especially at low levels, to SE as the second storm approached and started to move through the network. The wind speeds after 1730 CDT initially varied between 5 and 10 m/s and then decreased after 1800.

Time sections of divergence, vertical velocity, and relative vorticity from 1330 to 1800 CDT are given in Fig. 14. (The kinematic parameters could not be calculated at 1630 or 1700 CDT because of missing data). The flow from the surface to 700 m MSL was convergent for virtually the whole time. The data indicate that a minimum in convergence occurred as the early rain shower (which was light) slackened and moved out of the triangle and then increased again well ahead of the storm which moved in from the north. The maximum in convergence (2.1×10^{-4} sec^{-1}) was observed at 1400 CDT at 650 m MSL, with an average value for the column of -1.6×10^{-4} sec^{-1} at that time (Fig. 12a). There is a strong suggestion that the flow was strongly convergent in the upper part of the sub-cloud layer well before the rain first started and that the height of strongest convergence decreased as the rain approached.

The largest calculated vertical velocity was 6 cm/sec at 700 m at 1400 CDT (Fig. 14b). From 1330 CDT to after 1530 CDT the vertical velocities at 700 m MSL were all in excess of 3 cm sec^{-1}. At 1800 and 1830 the vertical motion at 700 m MSL was greater than 3 cm/sec and increasing.

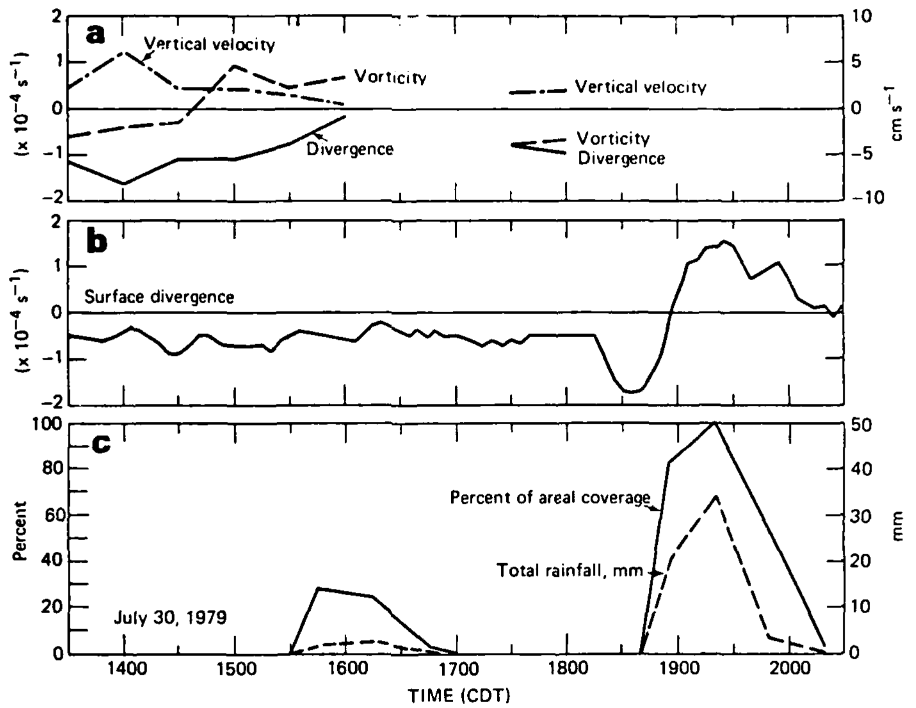


Figure 12. Same as Figure 3, but for 30 July 1979.

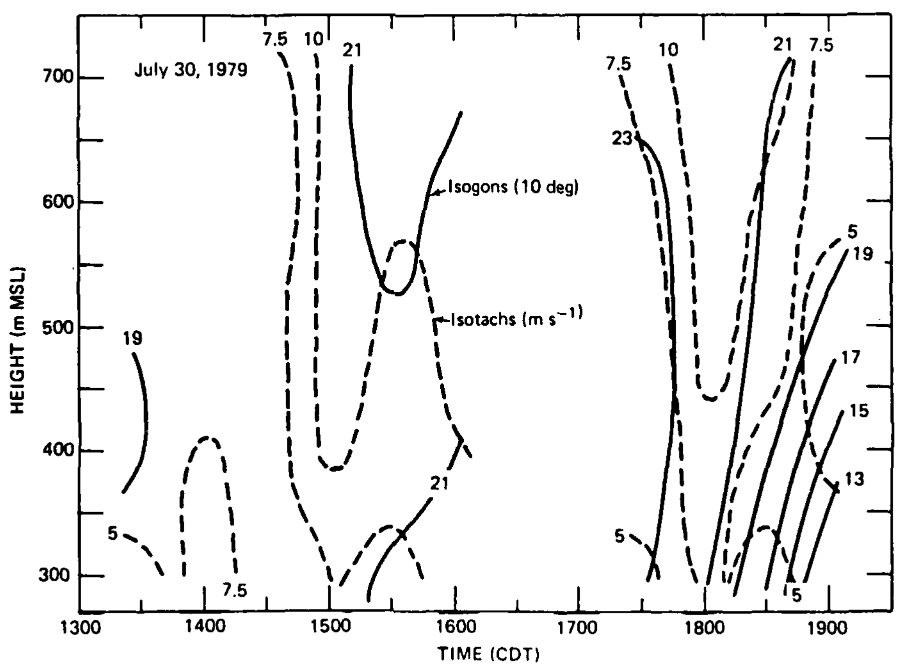


Figure 13. Same as Figure 4, but for 30 July 1979.

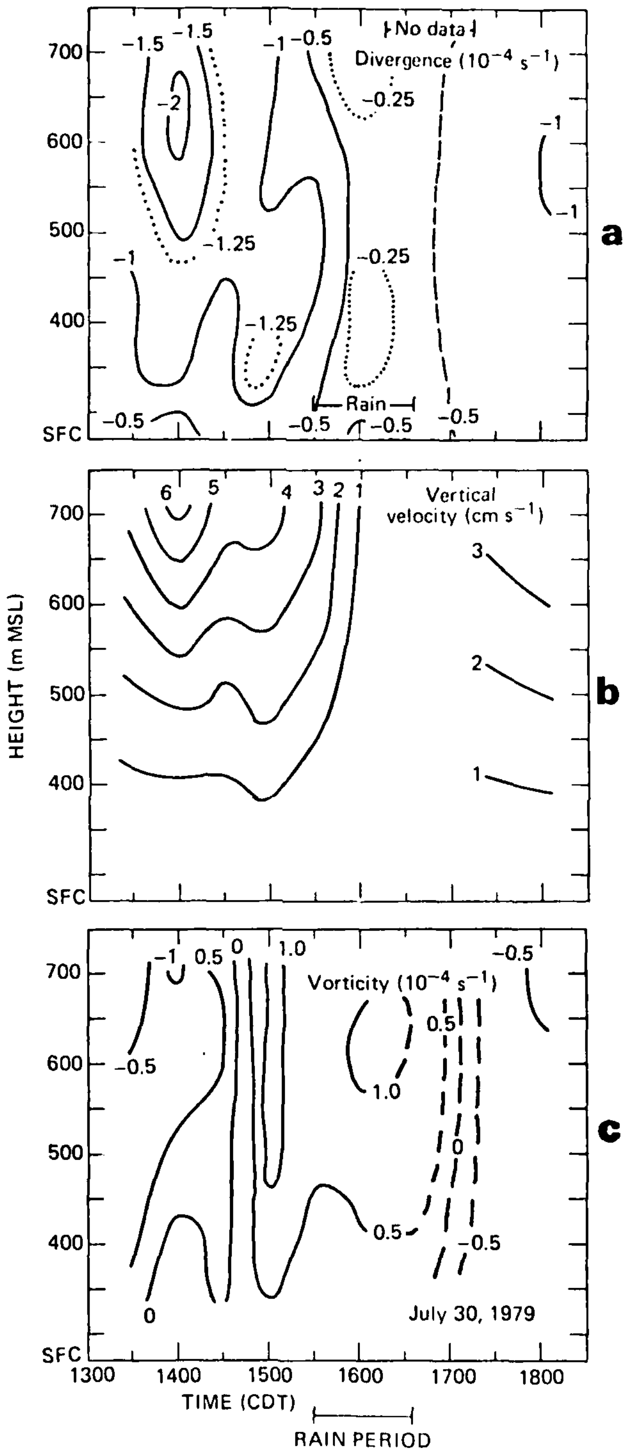


Figure 14. Same as Figure 8, but for 30 July 1979.

The relative vorticity from 1330 to 1430 CDT was mostly anticyclonic except below 400 m MSL at 1400 (Fig. 14c). Between 1430 and 1500 CDT the flow in the sub-cloud layer underwent a rapid transformation from anticyclonic vorticity to cyclonic with the column average changing from -0.3 to 0.9 x 10^{-4} sec^{-1} (Fig. 12a). The vorticity remained cyclonic during the first rain storm, with maximum value above 500 m MSL, but became anticyclonic after it ended.

The summary diagram in Fig. 12 clearly shows that the flow was convergent throughout the (roughly) lowest 400-450 m of the atmosphere prior to the first rain shower. Inflow in the surface layer decreased slightly during the light rain from 1530 to 1700 whereas the average for the sub-cloud layer decreased dramatically.

There was a slight increase in average layer convergence from 1730 to 1800 CDT, the last time for which divergence could be calculated. This was 45 minutes before the start of the second rain period in the triangle. The surface divergence, however, shows a typical gust-front signature after 1815 (Fig. 12b). The convergence increased by 1.3 x 10^{-4} sec^{-1} in 20 minutes, followed by a rapid decrease and switch to divergence for a total change of 3.4 x 10^{-4} sec^{-1} in 50 minutes. Divergence maximized at 1925 CDT, about the same time that the rainfall in the triangle maximized.

The divergence in sub-cloud and surface layers showed similar patterns until 1600 CDT, except that the upper-air convergence decreased about 30 minutes prior to any decrease in the surface convergence. A slight increase in upper-air convergence preceded the dramatic increase in surface convergence between 1815 and 1835 CDT, but only two upper-air observations were available after 1600.

Between 1430 to 1500 CDT there was a dramatic shift from anticyclonic vorticity to cyclonic vorticity in the flow in the triangle, as the column average changed from -0.3 to 0.9 x 10^{-4} sec^{-1} (Fig. 12a). The vorticity decreased somewhat but remained cyclonic from 1500 to 1600 CDT. After the first rain period, and before the start of the second, the vorticity was anticyclonic with a small decreasing trend between 1730 and 1800.

The CHILL radar, located on the east edge of the VIN network, detected several small echoes in the triangle beginning at 1511 CDT. However, no major echoes were observed within the triangle prior to 1525 CDT when the first echo core formed. (Echo cores are defined herein as echo clusters which maintained a definable reflectivity maximum for at least 15 minutes.) The number of radar cores and the percent of area covered by radar echoes increased from 1525 to 1611 CDT (Fig. 15c). Radar data after 1611 and to 1715 is sporadic because of frequent power surges and loss of power to the radar due to lightning. Prior to that time the percent of area covered by radar echoes and the percent of area covered by rainshowers, as indicated by the raingage

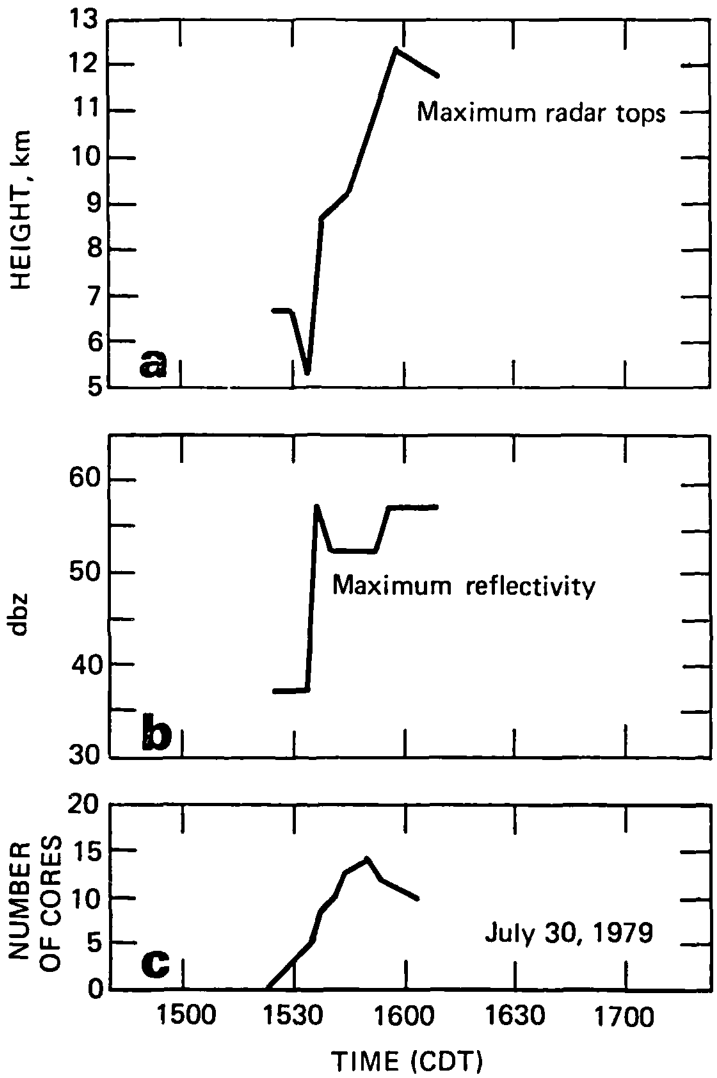


Figure 15. Time sequence of the characteristics of the radar echoes in the pibal triangle on 30 July: (a) top height of tallest echo; (b) strongest echo; (c) number of reflectivity cores. (See text for explanations).

network, were similar with slightly more radar echo coverage than surface rainfall coverage, as would be expected.

The maximum radar-measured tops, maximum reflectivity levels, and number of radar cores within the triangle changed little between 1525 and 1533 CDT (Fig. 15). After 1533 all three increased, primarily because of the advection of radar cores from the west into the triangle, rather than because of new echo development or growth of existing echoes in the triangle. The maximum tops and reflectivities after 1533 CDT occurred in those radar echoes which moved into the triangle and which continued actively to form new cores. The maximum tops increased from 5.25 km at 1533 CDT to 12.25 km at 1557 CDT. The maximum reflectivity until 1533 CDT was 37.5 dbz but after the advection of radar cores a maximum reflectivity of 57.5 dbz was measured several times.

The second rain period within the triangle began at 1825 CDT and quickly increased from an areal coverage of 10% to 100% by 1925 CDT (Fig. 12c). The average rain intensity increased from an areal average of less than 1 cm for the 30-minute period from 1800 to 1830 CDT to 27.8 cm for the 30-minute period from 1915 to 1945 CDT. The surface divergence field showed a typical gust front signature with an increase in convergence from -0.5 to -1.8 $\times 10^{-4}$ sec^{-1} from 1815 to 1825 CDT, and then divergence maximized (1.5×10^{-4} sec^{-1}) at 1925 CDT. The sudden increase of surface convergence beginning at 1815 CDT preceded the rain within the triangle by only 10 minutes.

10 August 1979

A cold front moved through the VIN network between 1300 and 1600 CDT and a short wave trough over Minnesota and eastern Nebraska at 0700 CDT moved across the network during the evening. At 1300 the cold front was to the west and extended from South Bend, Indiana, to Peoria, Illinois, to St. Louis, Missouri. By 1600 CDT the surface winds across the VIN network had shifted from west-southwest to west-northwest.

The maximum temperatures over central Illinois varied from 27 to 29 C, and the surface dew-point temperatures prior to and up to 6 hours after the passage of the cold front were 18 to 22 C. The 1300 CDT soundings at Champaign, Peoria, and Salem indicated that the Showalter Stability Index for the area was about -1 and the Lifted Index varied from 0 to -3. The precipitable water at Salem was 4.2 cm, while to the north, at Peoria and Champaign, it was 4.7 and 4.8 cm, respectively. Thus, the air over central Illinois was more moist than over the southern part of the State.

Scattered showers and thunderstorms were active over central Illinois from near noon to midnight. Individual rain cells moved from the west or west-northwest at 35 to 45 km/hr. Rain fell in the pibal triangle during three periods: 1) 1245 to 1340 CDT, 2)

1535 to 1620 CDT, and 3) 1735 to 1925 CDT (Fig. 16c). The heaviest rains over the VIN raingage network occurred in the period from 1700 to 2100 CDT, when an area of showers and thunderstorms traversed the network from the northwest corner to the south-central border. The most intense rains during this period occurred in the south-central and western portions of the network, only grazing the western raingages in the pibal triangle.

The early rains (1245-1340 CDT) were scattered light showers (maximum point rainfall of 0.65 cm or less) in advance of the cold front. The second rain period (1535-1625 CDT) was also due to widely scattered showers with the maximum point rainfall of 0.75 cm recorded south of the triangle. The third rainfall period began at 1735 CDT and was associated with the over-running cold front; the maximum point rainfall was 3.35 cm in the extreme south-central part of the raingage network.

Pibal observations began at 1000 CDT and continued to 1700 CDT, with some observations missing at 1300 and 1330 CDT. From 1000 to 1300 CDT the low-level winds were mostly from the west and west-southwest with winds above 350 m MSL more west to west-northwest (Fig. 17). At about 1400 CDT the wind at 300 m MSL shifted to north of west, asociated with the passage of the cold front through the VIN network. The winds continued veering to a more northerly component for the remainder of the observational period. The wind speeds after the passage of the cold front were relatively light, generally less than 5 m/s.

The flow was convergent from just above the surface to 700 m MSL at 1000 CDT, and continued so above 500 m until 1200 CDT (Fig. 18a), when it became divergent. During the rain period from 1245 to 1340 CDT the surface wind field was slightly convergent, but the sub-cloud layer winds above were divergent before and after these first rains, and probably during them as well. Above 450 m MSL, the wind field became convergent just before 1500 CDT, at least 30 minutes prior to the start of rain at the surface and remained so through most of the second rain period. The surface winds on the other hand were predominantly divergent, except for a very short time. Convergence was again observed from the surface to 350 m MSL and above 500 m MSL at 1700 CDT, 35 minutes prior to the start of heavy rains in the triangle, and about 15 minutes before the rain entered the VIN network at the northwest corner.

The compensating vertical motion shows strong upward motion at 1000 CDT with a rapid reversal by 1030 CDT (Fig. 18b). The downward motion continued through 1230 CDT, and probably throughout the first period of rain. Weak upward motion was noted from 1500 to 1600 CDT above 600 m MSL, during and just prior to the second rain period. There was upward vertical motion again near the surface and above 550 m MSL at 1700 CDT, 35 minutes before rain began in the triangle for the third time on this day.

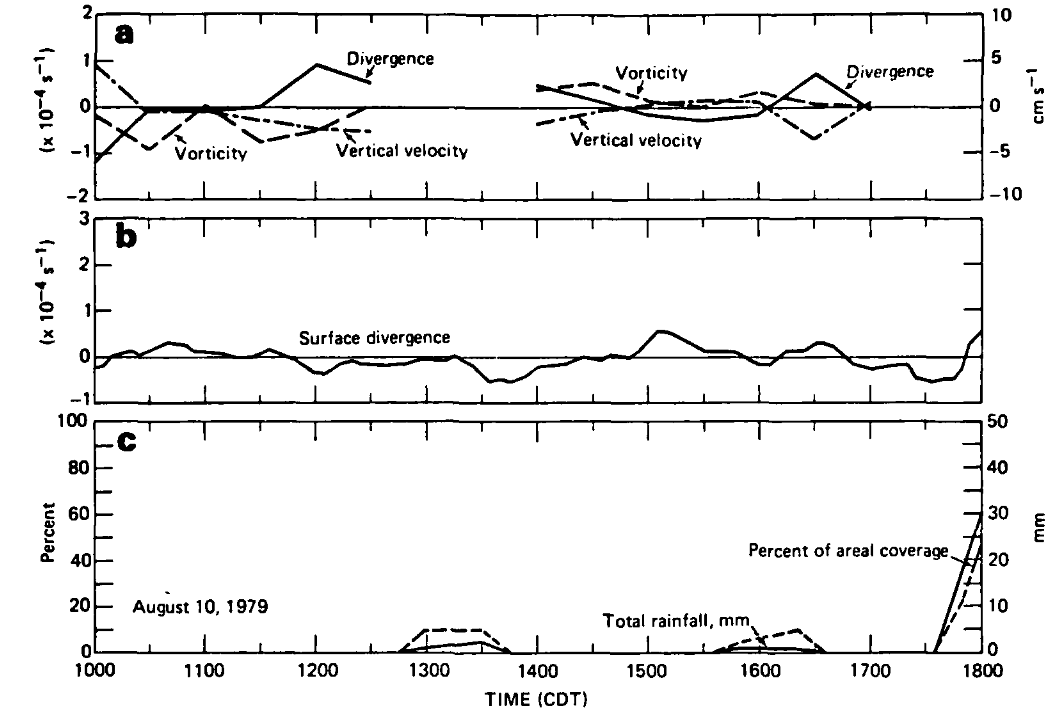


Figure 16. Same as Figure 3, for 10 August 1979.

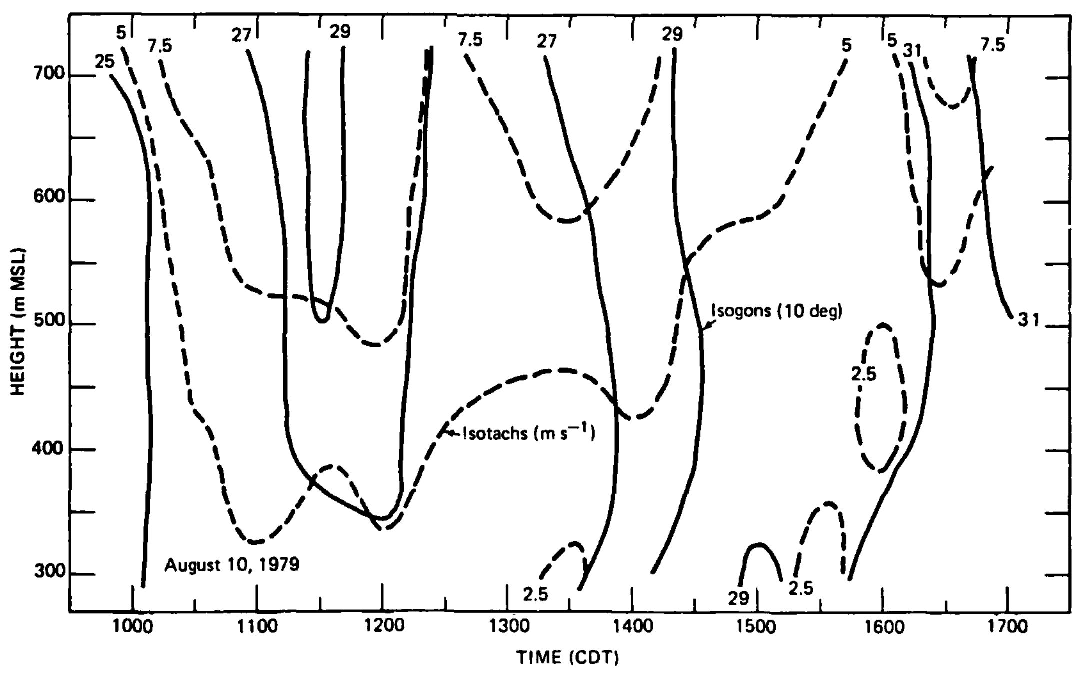


Figure 17. Same as Figure 4, for 10 August 1979.

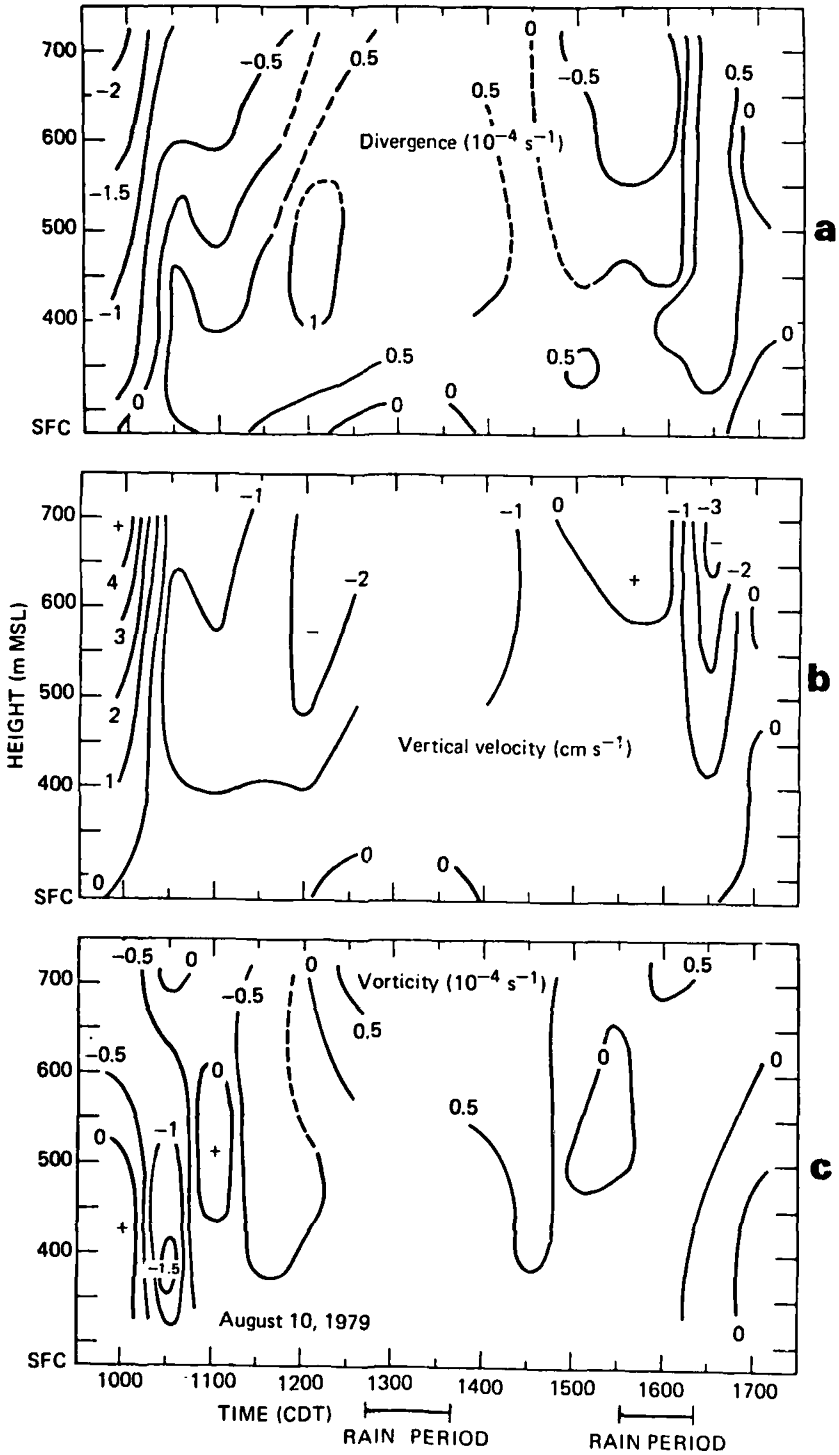


Figure 18. Same as Figure 8, for 10 August 1979.

The vorticity was cyclonic in the low levels at 1000 CDT, but became anticyclonic at 1030 CDT. Except for some weak cyclonic vorticity between 450 and 600 m MSL at 1100 CDT, the flow had anticyclonic vorticity in the sub-cloud layer until the start of the first rain period. After the first rain period the vorticity was mostly cyclonic.

The "summary" diagram of the surface and upper-air features (Fig. 16), shows that the surface divergence field tended to become convergent beginning at 1135 CDT. The surface divergence changed from 0.1×10^{-4} sec^{-1} at 1135 CDT to -0.4×10^{-4} sec^{-1} at 1205 CDT, about 40 minutes before rain began anywhere in the dense raingage network. However, the column average divergence was either near zero or divergent after 1000 CDT, with compensating downward vertical motion (Fig. 16a). There apparently was no coupling between the near-surface and surface kinematics. A second increase in convergence occurred at the surface between 1320 and 1335 CDT which was followed by return to divergent surface flow by 1440 CDT. This second "surge" of convergence ended 110 minutes prior to the second rain period, and was most likely related to convection occurring just east of the triangle. After the first rain period the average divergence from the surface to 700 m MSL became less divergent, and between 1500 and 1600 CDT the average sub-cloud flow was convergent. A comparison of the curves for sub-cloud and surface divergence in Figs. 16a and b suggests that the surface and upper-air kinematics were coupled after 1600 CDT.

18 August 1979

At 1300 CDT on 18 August a cold front was centered in a general pressure trough which extended from southwest Michigan to central Nebraska. This cold front moved slowly southeast during the day, sagging as far south as Champaign by 0100 CDT on 19 August. A series of short-wave troughs embedded in the long wave circulation at 700 and 500 mb, slid across Illinois and flattened an anticyclonic circulation centered over the southern Gulf States. The flow at 850 mb throughout the day was from the southwest.

The maximum surface temperatures over central Illinois ranged from 29 to 33 C, with dew-point temperatures of 21 to 24 C. The air mass south of the front was moist, as indicated by the 1300 CDT precipitable water of 4.2 cm at Salem and Champaign and 3.6 cm at Peoria. The atmosphere was unstable with the 1300 Showalter Stability Indices of -2 and Lifted indices ranging from -4 to -6 at the three radiosonde sites.

Ahead of the cold front, scattered showers and thunderstorms developed in central Illinois at 1700 CDT, and continued through the evening. The precipitation cells moved from the west at 35 to 40 km/hr. As the front moved southward, the areal coverage and intensity of the convective activity increased, and by 2000

CDT a general area of showers and thunderstorms extended on an east-west line from central Indiana to west-central Illinois. The earliest rain in the VIN network was 10 km east of the pibal triangle, and a rainstorm initiated over the center of the triangle shortly before 1930 CDT. Rain continued in the triangle until 2120 CDT (Fig. 19c). The storms over the dense raingage network moved east, with new storms initiating north and south of the triangle between 2000 and 2100 CDT.

Pibals were released from 1430 to 2000 CDT with the 1730 and 1830 CDT measurements missing. The winds for this period were usually between 220 and 230° with wind speeds generally in excess of 7.5 m/s (Fig. 20). A maximum in wind speed was measured above 550 m MSL at 1530 CDT, which corresponded in time to a maximum in the convergence field and strong upward vertical motion (Fig. 21). The wind speeds in both the upper and lower levels of the sub-cloud layer began to increase at approximately 1700 CDT and reached maximum at 1930 CDT, about the time that rain started in and west of the triangle. Between 2000 and 2030 CDT the wind speed decreased and the wind direction shifted from 230 to 310° at 300 m MSL and from 240 to 270° at 700 m MSL. This sudden shift in wind direction was coincident in time with the peak in the rainfall and apparently was a response to convective activity in and/or just outside of the triangle.

The wind field from the surface to 700 m MSL was mostly convergent, except in the upper levels at 1430 CDT and between 350 and 450 m MSL at 1630 CDT (Fig. 21a). At 1800 CDT the convergence rapidly increased, especially between 350 and 550 m MSL, reaching nearly 4×10^{-4} sec^{-1} shortly after 1900. This increase to strong convergernce preceded the start of rain in the pibal triangle by nearly 90 minutes. The compensating vertical motion (Fig. 21b) was mostly upward during the afternoon and evening. The strongest upward motion (14.9 cm/sec at 1900 CDT) was at 700 m MSL from 1900 to 1930 CDT, just prior to, and coincident with, the onset of precipitation.

Prior to 1800 CDT the relative vorticity alternated between cyclonic and anticyclonic in the region from 350 to 700 m MSL (Fig. 21c). After 1800 CDT, however, it was increasingly more cyclonic, reaching over 4×10^{-4} sec^{-1} between 400 and 650 m MSL at 2000 CDT. The strong increase in cyclonic vorticity started about an hour before the start of rain in the dense raingage network.

There was a general increase in surface convergence from early afternoon until 1945 CDT when the surface wind field was affected by thunderstorm outflows (Fig. 19b). This increase in surface convergence was mirrored by an even stronger increase in convergence in the column from 350 to 700 m MSL (Fig. 19a). The average divergence in the sub-cloud layer changed from $+0.3 \times 10^{-4}$ sec^{-1} at 1500 CDT to -3.4×10^{-4} sec^{-1} at 1900 CDT. The average vorticity in the layer from 350 to 700 m MSL was weakly anticyclonic until 1800 CDT, but then became increasingly cyclonic, mirroring the increase in convergence. The strong

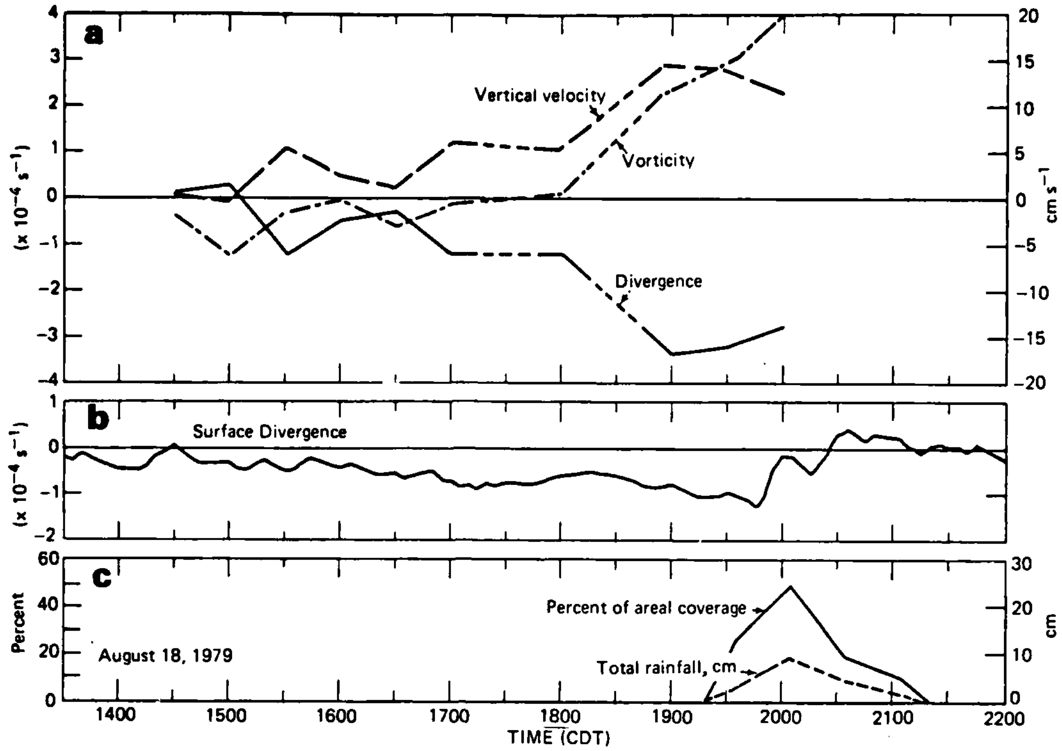


Figure 19. Same as Figure 3, for 18 August 1979.

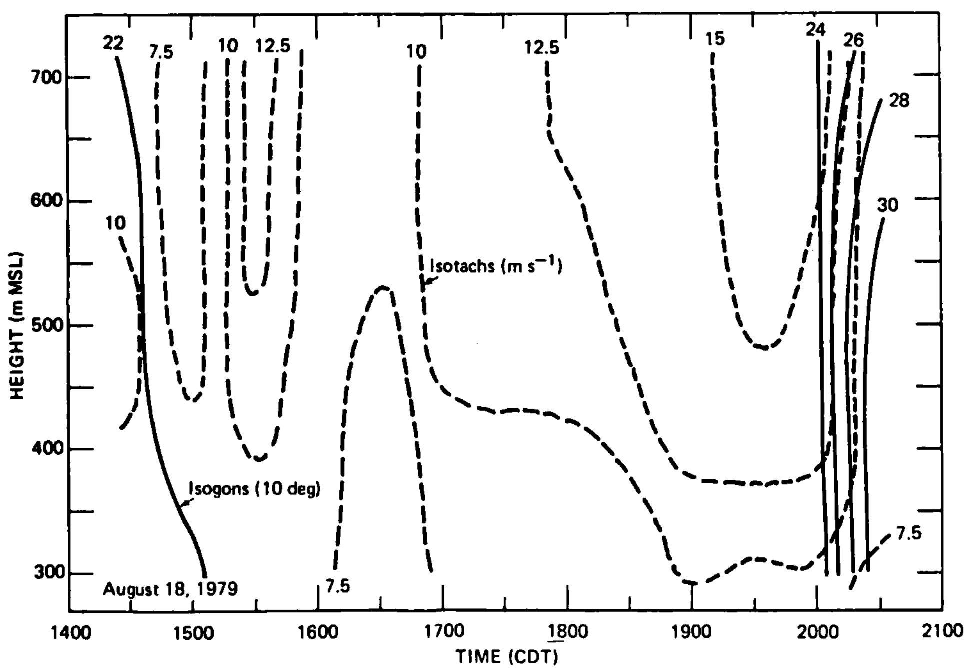


Figure 20. Same as Figure 4, for 18 August 1979.

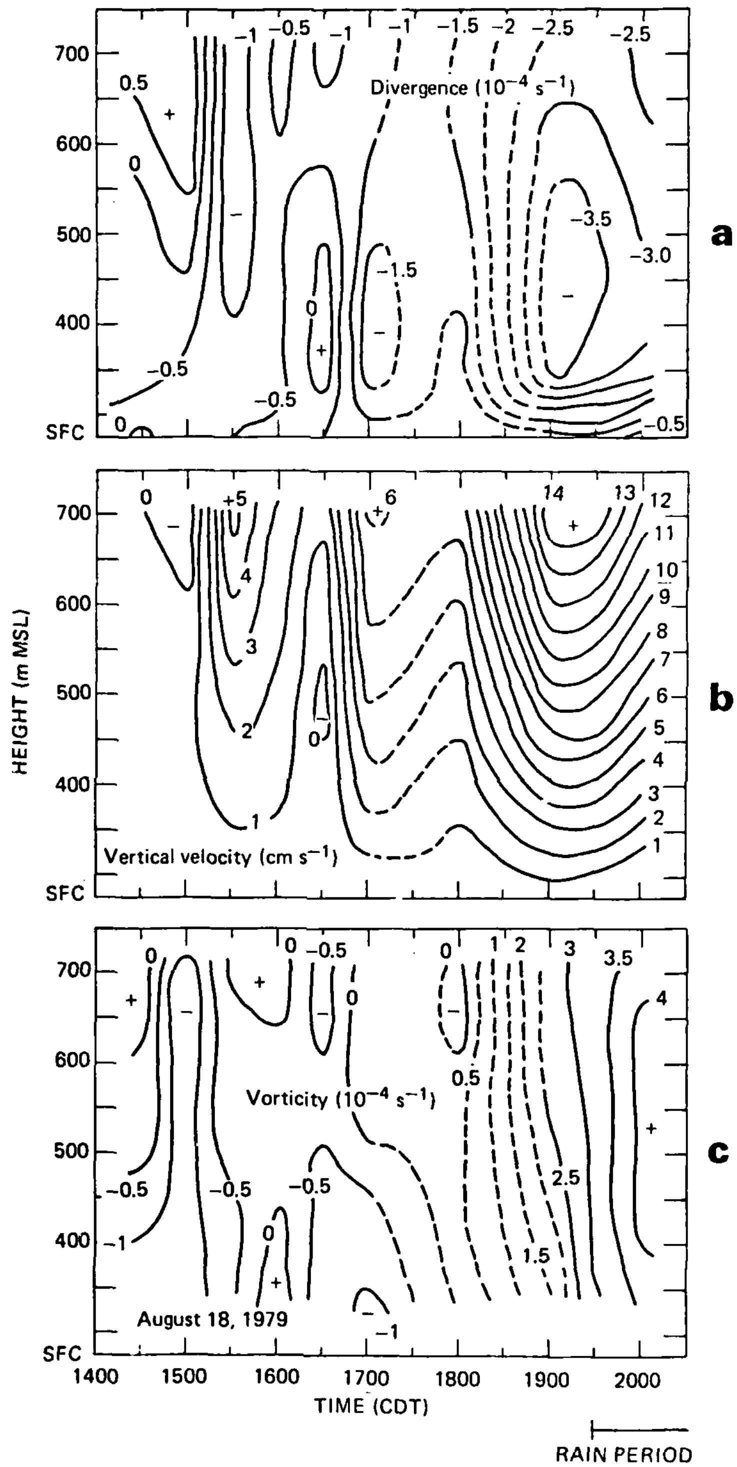


Figure 21. Same as Figure 8, for 18 August 1979.

organization of the surface and sub-cloud layer flow preceded the start of precipitation within the triangle and over the dense raingage network but probably was coincident with the organization of the convection.

Only 50% of the triangle was covered by precipitation at any given time, and only 63% of the stations in the triangle received rain. However, 100% of the stations in the downstorm area on the dense raingage network experienced rains.

19 August 1979

The VIN network was embedded in a warm tropical air mass with surface dew-point temperatures ranging from 20 to 24 C on 19 August. A stationary front was oriented on an east-west line across northern Illinois. This front had drifted south to central Illinois as a cold front during the early morning hours, but then drifted back north during the day. At 1300 CDT it was located between Chicago and Champaign. Light southerly winds with maximum temperatures between 30 and 35 C were observed during the afternoon and early evening hours. The upper-air flow was light zonal with a train of weak short waves drifting through Illinois. This train of short waves continued to flatten the anticyclonic circulation centered over the Gulf States, causing general westerly flow over Illinois at 700 and 500 mb. The flow at the surface and up through 850 mb was from the south and southwest.

The air mass was moist with precipitable water content of 3.7 cm at both Peoria and Champaign at 1300 CDT. The atmosphere was also unstable, with Showalter Stability Index of -1 and Lifted Indices of -4 and -5 at Champaign and Peoria, respectively. No rain occurred in the triangle from 1330 to 1930 CDT, the period when pibal observations were made. Some light rains (less than 1.3 mm) did occur, however, about 10 to 20 km east of the triangle between 2000 and 2300 CDT.

The winds in the sub-cloud layer at 1300 CDT were 240° and backed to 200° by 1500 CDT. For the remainder of the observational period the wind direction varied from 190 to 210° (Fig. 22). The wind speeds prior to 1700 CDT varied between 2 and 6 m s^{-1}, but increased after 1700 CDT to 10 to 12.5 m/s above the surface.

The surface flow was weakly divergent except for some minor convergence between 1740 and 1845 CDT (Fig. 23b). The column average values of relative vorticity indicates a "cycling" between cyclonic and anticyclonic paralleled by similar changes in divergence, (Fig. 23a), indicating little organization in the wind field over the network during the afternoon or early evening of 19 August. The temporal variability in the kinematic fields is also evident in the time-height profiles in Fig. 24. The divergence was generally weak and changed sign several times at all levels in the sub-cloud layer. The most organized period was

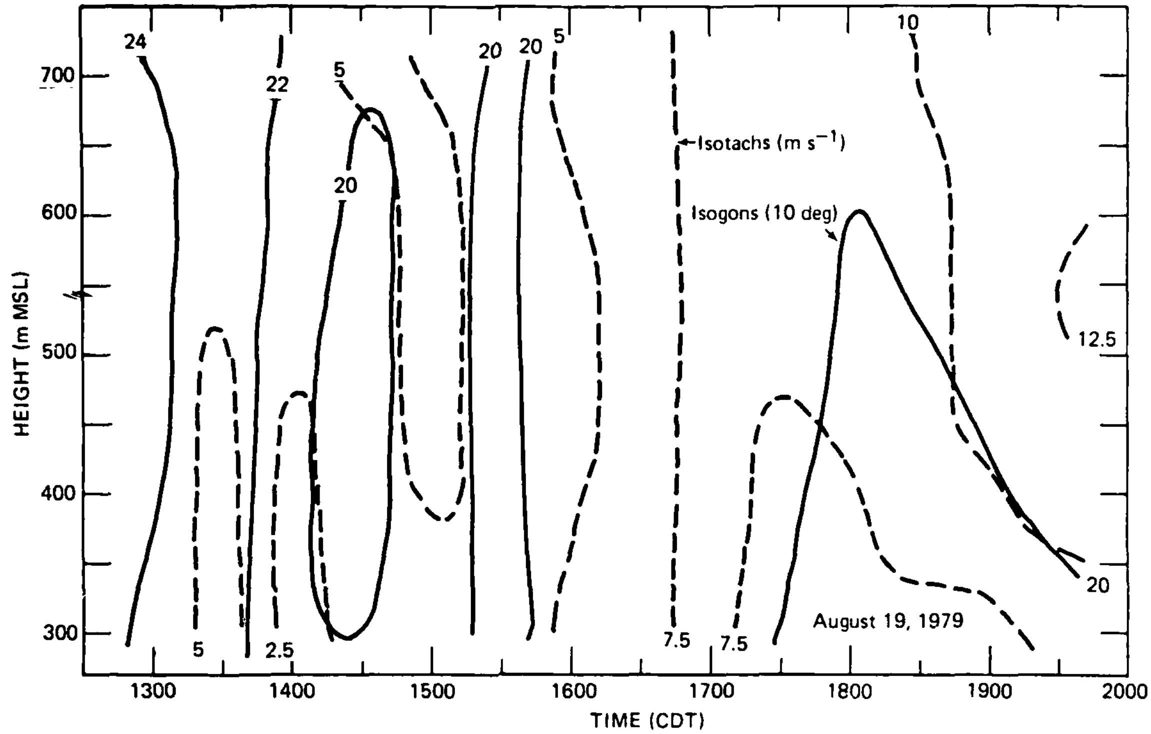
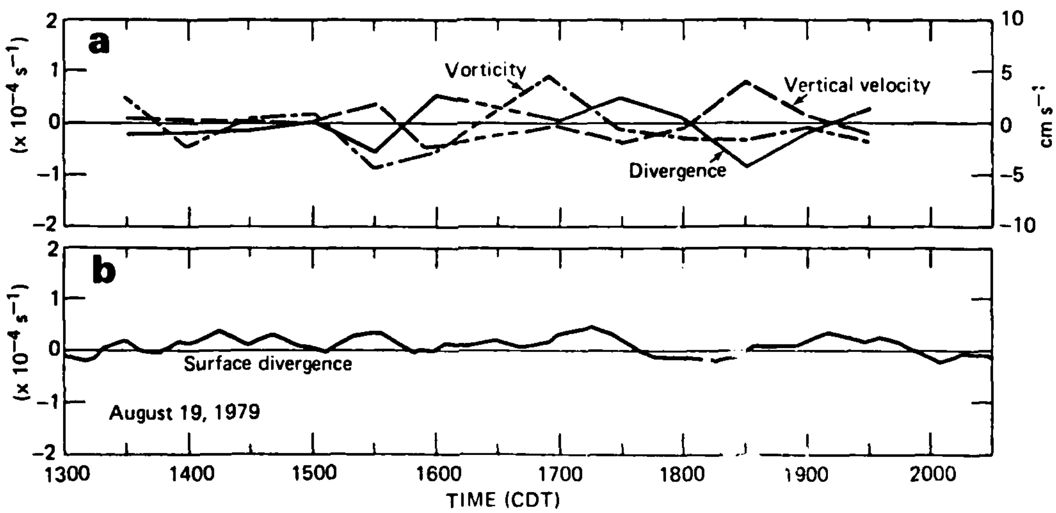


Figure 22. Time-height analysis of wind direction (isogons) and wind speed (isotachs) in sub-cloud layer on 19 August 1979.



NO RAIN IN TRIANGLE

Figure 23. Time series of (a) column-average (300-700 m MSL) divergence and vorticity (10^{-4} s^{-1}), and vertical motion at 700 m MSL, and (b) surface divergence over the pibal triangle, on 19 August 1979.

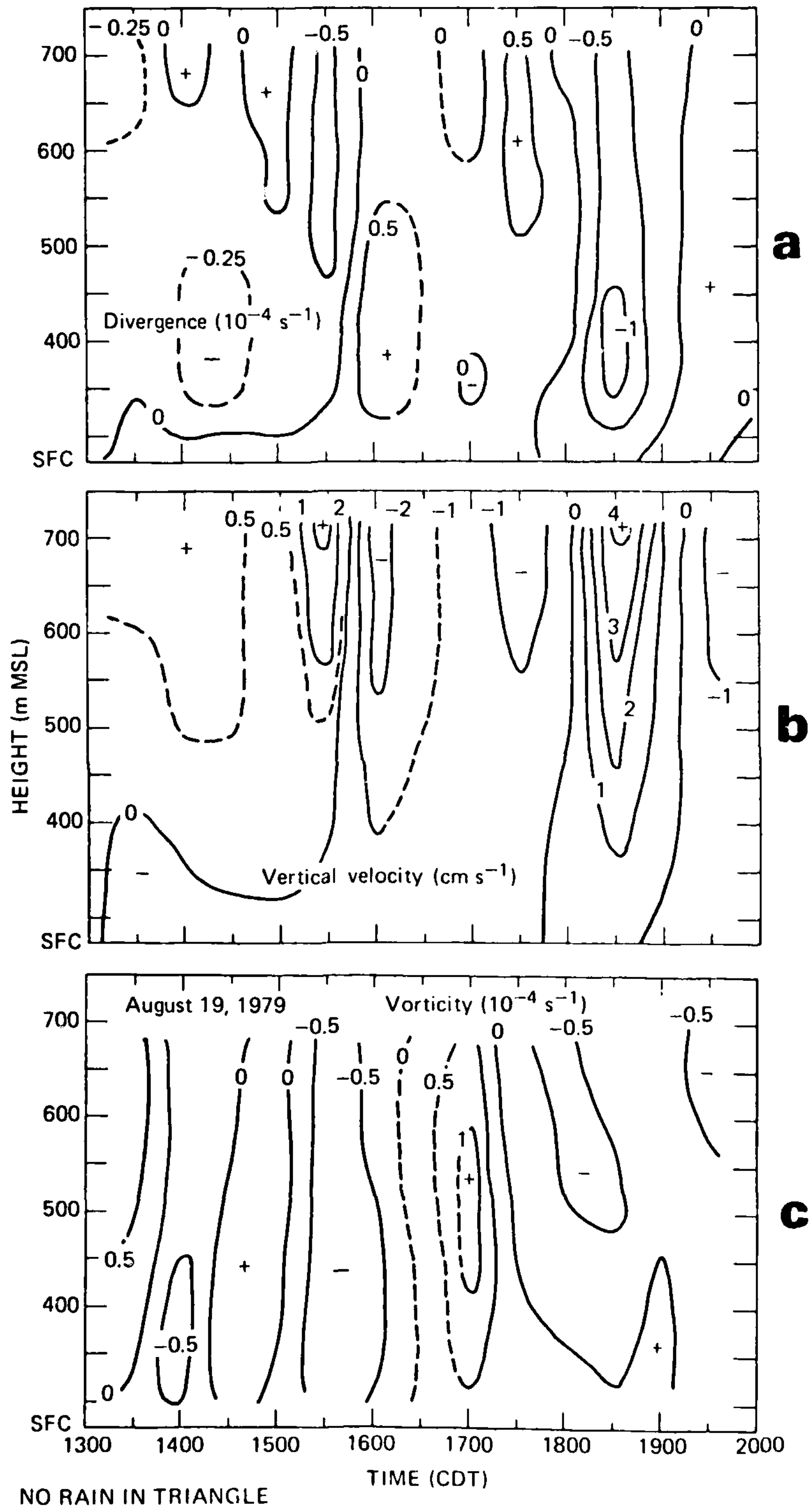


Figure 24. Same as Figure 8, but for 19 August 1979.

at 1830 CDT when both the surface and the upper-level flows were convergent. The convergence maximized between 350 and 450 m MSL between 1800 and 1900, the only time that the surface flow was even weakly convergent. The vertical motion compensating for the divergence maximized with an upward motion of 4 cm sec^{-1} at 1800 CDT (Fig. 24b), and a maximum downward vertical motion of -2.4 cm sec^{-1} at 1600 CDT.

The relative vorticity was even more variable than the divergence field, shifting about every 30 to 60 minutes between cyclonic and anticyclonic, at least to 1730. After 1730 CDT the flow primarily had anticyclonic vorticity. The vorticity during the period of observation ranged from -0.9 to 1.1 x 10^{-4} sec^{-1}.

22 August 1979

During the morning of 22 August a warm front moved north across the VIN network, and continued into Wisconsin and Michigan. The warm front was associated with a low pressure area which moved from a position in northeast Kansas at 0700 CDT to west central Wisconsin by 2200 CDT. The upper air was characterized by a trough over western Iowa and Missouri which deepened during the day, but remained stationary.

During the afternoon the VIN network was embedded in warm, moist, tropical air. The afternoon maximum temperatures ranged from 26.5 to 29 C, and the surface dew-point temperatures hovered between 21 and 22 C. The precipitable water at 1300 CST ranged from 3.2 cm at Salem in southern Illinois to 3.6 cm at Peoria. The Lifted Index indicated that the atmosphere was conditionally unstable with values of 0 at Salem, -3 at Champaign, and -5 at Peoria.

Showers and thunderstorms were detected along the Mississippi River at 1335 CDT by NWS WSR 57 radars. This convective activity moved east at 35 to 45 km/hr, with individual convective entities moving from the west-southwest at the same speed. The showers anbd thunderstorms moved onto the VIN dense raingage network at 2000 CDT. Point rainfall amounts in excess of 2.5 cm were observed in 1-hour periods from 2000 to 2300 CDT over the northern part of the dense raingage network, north of the pibal triangle. Only light rainshowers, 5-minute amounts of 4 mm or less, were observed anywhere in the network between 2000 and 2035 CDT. After 2035, heavier rains moved in, and also formed over, the network, primarily over the northern third.

The rain did not begin in the triangle until after 2110 CDT (Fig. 25c), about 70 minutes after rain was first observed over the dense raingage network. Within the triangle, less than 20% of the raingages received rain in any 30-minute period, and the total rain at all the raingages within the triangle in any 30-minute period was less than 3 cm.

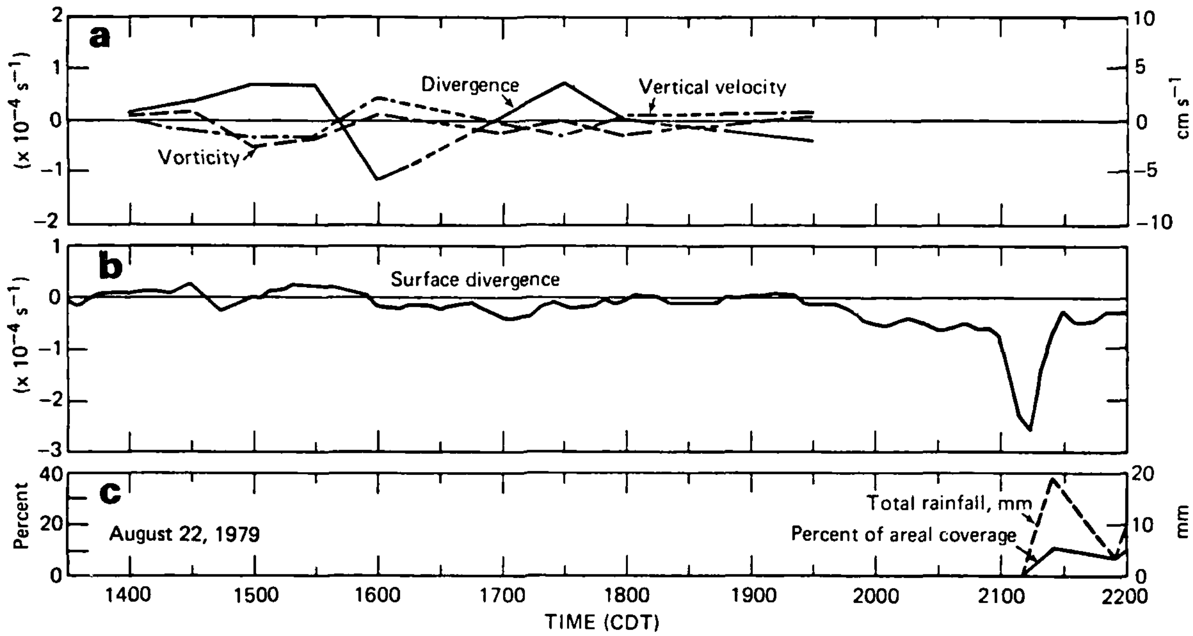


Figure 25. Same as Figure 3, for 22 August 1979.

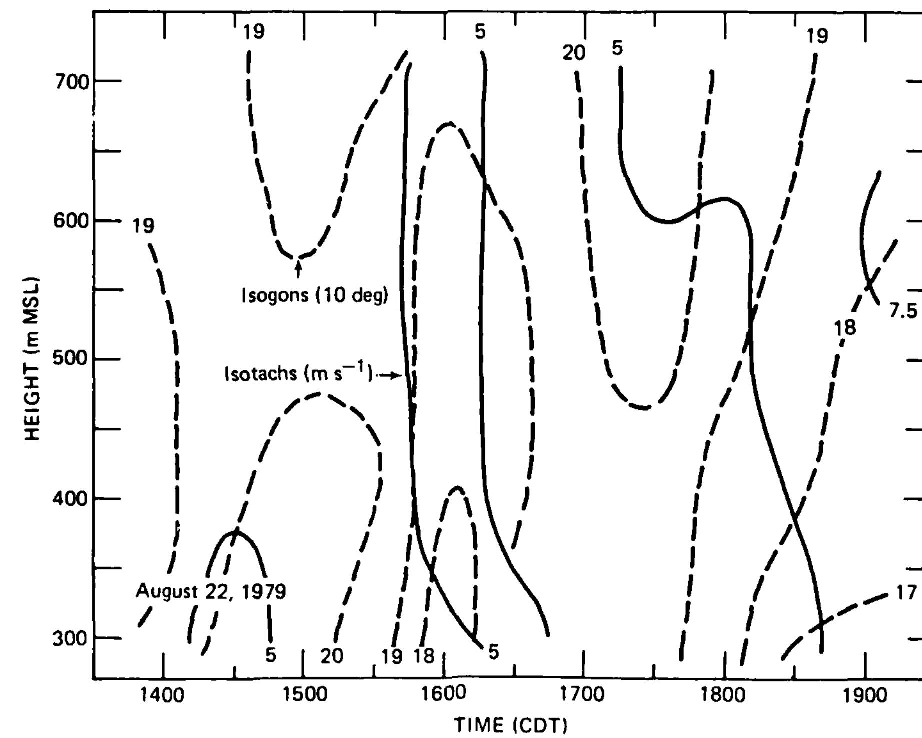


Figure 26. Same as Figure 4, for 22 August 1979.

Pilot-balloon measurements were taken from 1400 to 1930 CDT with no measurement made at 1630, and measurements missing at one of the sites at 1830. The boundary layer winds were generally from 190° to 200° during the afternoon, with speeds of 3 to 6 m/s (Fig. 26). After 1800 the winds backed from 190° to 170° in the low levels, and the speeds were greater than 5 m/s with a maximum of 7.5 m/s at 600 m MSL at 1900 CDT.

The wind field in the sub-cloud layer alternated between divergent and convergent flow during the afternoon and evening (Fig. 27a), which is reflected in a similar cycling in compensating vertical motion (Fig. 27b). The highest upward motion, 5 cm/sec, occurred at 1600 CDT, and the highest downward motion, -2.9 cm/sec, at 1730 CDT, both at the top of the sub-cloud layer. The flow in the triangle during most of the afternoon had only weak vorticity, alternating between anticyclonic and cyclonic (Fig. 26c). In general anticyclonic vorticity was associated with diviergence and cyclonic with convergence.

The cycling between convergence and divergence occurred in the sub-cloud layer with a frequency of approximately an hour, until 1700. After that (to 1930 at least), the flow was very weakly convergent, with indications that convergence was on the increase (Fig. 25a).

The surface divergence field also alternated between weak convergence and divergence during the afternoon (Fig. 25b). A gradual increase in convergence started at 1945 more than an hour before rain occurred within the triangle and shortly before the first rain in the raingage network. A typical thunderstorm gust-front signature occurred in divergence starting 10 minutes before the start of rain in the triangle.

The pibal measurements ceased nearly 1 1/2 hours before rain started in the pibal triangle. However, there is evidence in both the column average divergence (Fig. 25a) and in the time height profiles (Fig. 27a) that the increase in convergence associated with the developing or advecting convection in the early evening may have started earlier in the sub-cloud layer than it did at the surface.

23 August 1979

A double cold front system pushed across Illinois during the daylight hours of 23 August, with passage across the VIN network between 1600 and 1700 CDT. The upper-air flow across Illinois on this day was southwesterly. The air mass in advance of the cold front had precipitable water content of 3.2 cm. In addition, the air mass was conditionally unstable, with a Showalter Stability Index of 0 and a Lifted Index of -2. The maximum temperatures, which occurred prior to the cold front passage, varied between 26.5 and 29.5 C, and the surface dew-point temperatures ranged from 19 to 21 C.

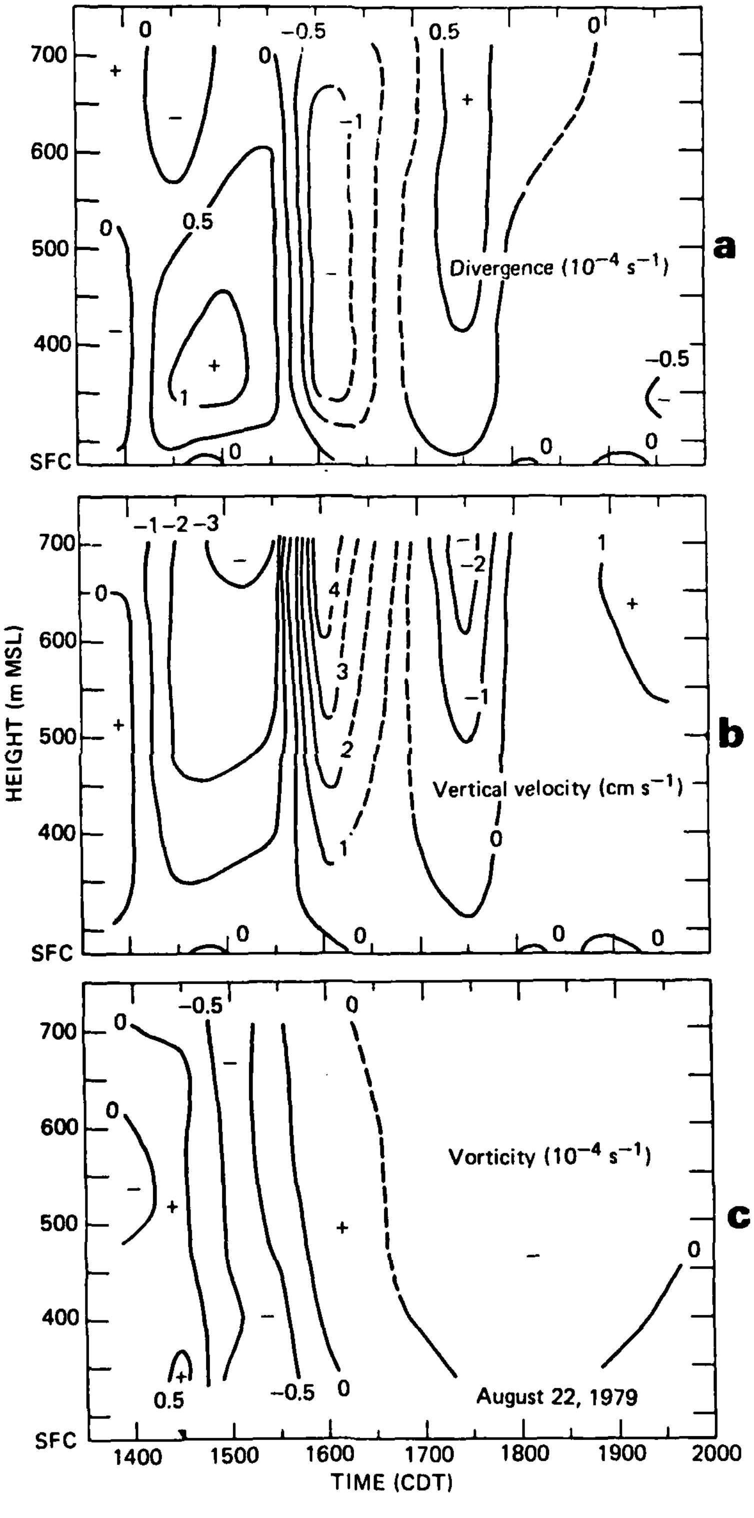


Figure 27. Same as Figure 8, for 22 August 1979.

Some scattered light rainshowers fell in advance of the cold front over the dense raingage network, beginning at 1335 CDT. Showers tended to generate just west of the network and move east. The heaviest rains fell on the east-central edge of the raingage network between 1600 and 1800 CDT with hourly measurements between 2.3 and 2.5 cm. Scattered light showers and thunderstorms continued over the extreme eastern part of the raingage network until 2010 CDT. The rain in the triangle began at 1435 CDT and ended at 1620 CDT (Fig. 28c). The rains which occurred within the triangle were from showers which initiated 5 to 10 km to the west at 1415 CDT and then moved into the triangle.

Pibals were released from 1330 to 1900 CDT, but wind measurements at one or more of the three sites were not available at 1600 and 1630 and after 1800. The winds from 300 to 700 m MSL were from the SW with speeds between 4 and 9 m/s until 1530 (Fig. 29). The wind veered to the west by 1700 CDT and continued to veer to north of west. Maxima in wind speed occurred just before the rain started and just after it ended.

The sub-cloud layer flow was weakly divergent at 1330 CDT, but by 1400 had become convergent (Fig. 28a). The sub-cloud convergence increased in magnitude at all levels up through at least the first 30 minutes of the period that rain was occurring within the triangle (Fig. 30a). The surface winds in the triangle were convergent, even when the sub-cloud flow was divergent (Fig. 28b). After the frontal passage (1600 to 1700 CDT), the sub-cloud flow became divergent between 350 and 550 m MSL, and then again become convergent by 1800 CDT.

The compensating vertical motion through most of the period was upward, as would be expected, except for some slight downward motion at 1330 and 1730 CDT. The upward motion maximized at 10.3 cm/sec at 1530 CDT during the time that rain was falling within the triangle.

The relative vorticity pattern prior to 1500 CDT varied rapidly from cyclonic to anticyclonic and then back to cyclonic. After the frontal passage the flow was anticyclonic, but there was evidence of shift back to cyclonic above 550 m MSL at 1800.

The surface flow was convergent from 1330 to 1855 CDT (Fig. 28c). There was an increase in convergence from -0.05×10^{-4} sec^{-1} between 1400 and 1415, about 20 minutes prior to the initiation of rain within the triangle. Another increase occurred between 1430 and 1440 CDT. Both of these "surges" could have been due to outflow from the shower and thunderstorm activity within or outside of the triangle. The flow in the layer from 350 to 700 m MSL was mostly convergent during the periods when adequate observations were available. Before and through the middle of the rain period within the triangle the flow was well organized, with strong upward motion, cyclonic flow, and convergence from the surface through 700 m MSL (Fig. 30). After the rain ended in the triangle (but was still occurring to the east), the vertical motion at 700 m MSL was weak and the relative

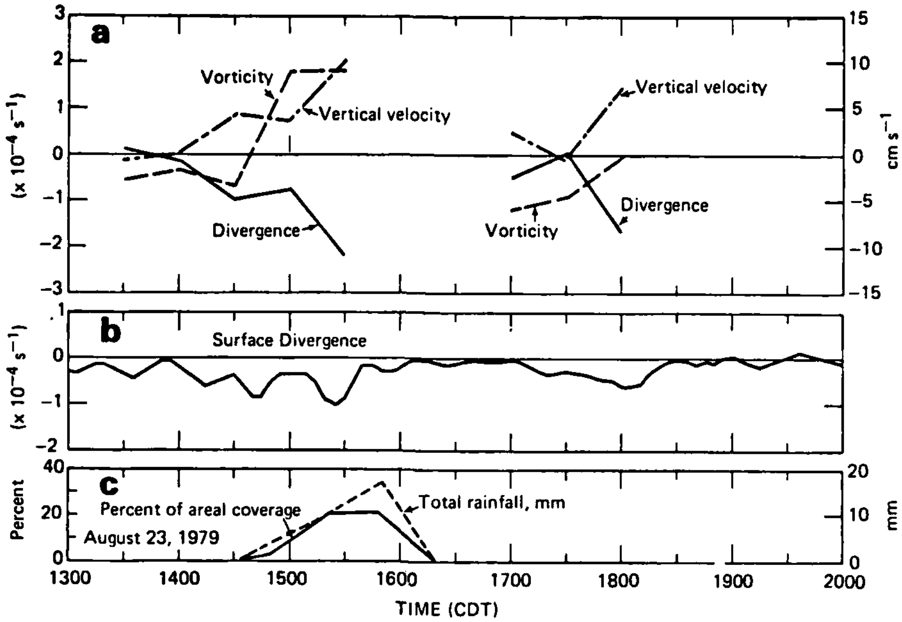


Figure 28, Same as Figure 3, for 23 August 1979.

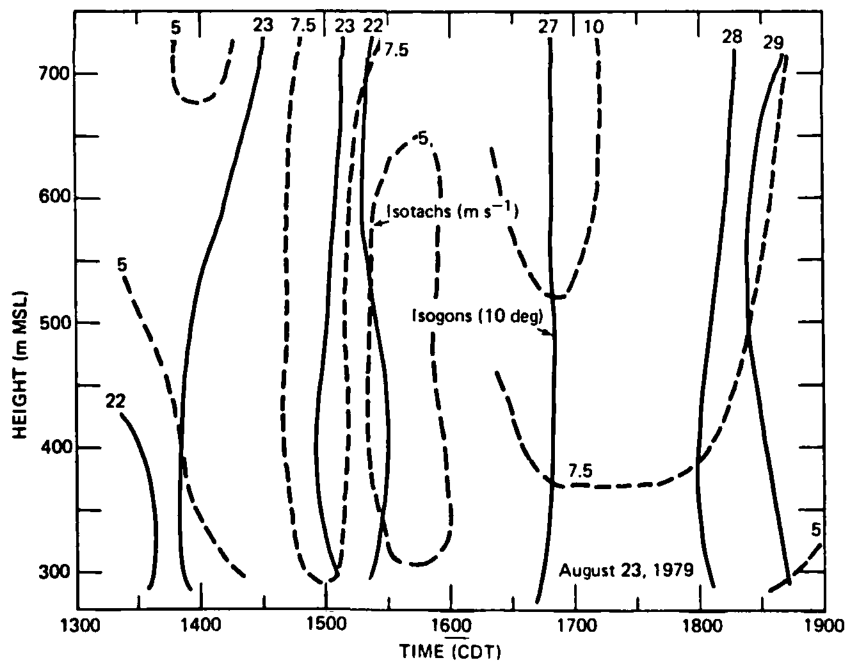


Figure 29. Same as Figrue 4, for 23 August 1979.

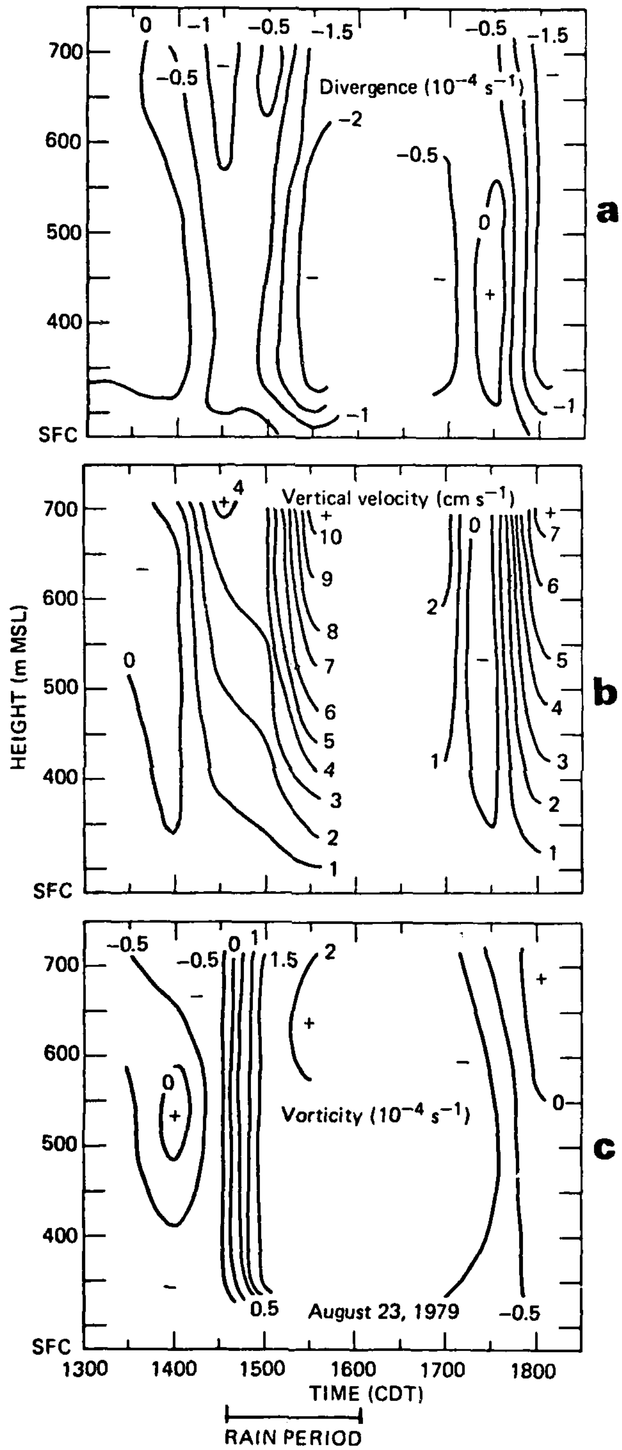


Figure 30. Same as Figure 8, for 23 August 1979.

vorticity had shifted from cyclonic to anticyclonic. By 1800 CDT there was a trend toward less anticyclonic vorticity, more convergence, and greater upward motions at the 700 m MSL level.

SECTION III

SYNTHESIS AND DISCUSSION

The kinematic parameters of divergence and vorticity in the lowest 450 m of the atmosphere were calculated for a 750 km^2 area from wind measurements obtained using pilot balloons. The area for which the analysis has been made is triangular, as defined by the three stations at which the pibal measurements were made. These and similar data for the surface have been analyzed for nine days of the summer of 1979. Most of the observations were made during the afternoon and early evening hours during periods when tropical air masses overlay the VIN observational network. The maximum surface temperatures on these days ranged from 26.5 to 35 C, and the surface dew-point temperatures varied from 18 to 24 C, approximately normal for temperature but more humid then normal. (The average dew-point for central Illinois is 18 C during July, 17 C in August.) The precipitable water content from the surface to 400 mb ranged from 3.2 to 5.3 cm, higher (by as much as 77% at the extreme) than the normal precipitable water over central Illinois during July or August (Lott, 1976).

The synoptic characteristics of the nine days, using the classification scheme developed by Vogel (1977), indicated three days with squall zones (13 July, 18 and 22 August), three days with cold fronts (14 July, 10 and 23 August), two days with squall lines (24 and 30 July), and one air mass day (19 August). Such systems contribute over 90% of the summer's rainfall in the Midwest (Vogel and Huff, 1978). Except for some light scattered showers 10-20 km east of the pibal triangle on 19 August, the days were characterized by convective systems which organized in or moved across central Illinois.

The precipitation within the triangle was highly variable. On 19 August no precipitation was recorded at all, and on two of the nine days (24 and 30 July) over 390 mm of rain accumulated in the raingages within the triangle. Large spatial and temporal variability of rain is expected during the summer over central Illinois, where, on the average, 20% of the storms produce 70% of the rain (Huff and Schickedanz, 1970). Thus, the rains observed within the VIN network on the nine days studied were not unusual, but rather were typical of summer rains in the Midwest.

The sub-cloud layer divergence, vertical velocity, and vorticity, for the period from up to 2 hours prior to the onset of precipitation to the end of rain, were analyzed to determine the relationship, if any, between sub-cloud kinematic parameters and precipitation. The study sought a "predictor" with lead time of more than the 5 minutes found by Watson and Holle (1982) for Illinois using surface divergence. Watson and Holle had determined that it was possible to "now-cast" rainfall in Florida using surface divergence with a lead time of 35 minutes, significantly longer than a similar scheme provided for Illinois.

A major factor contributing to the disagreement in the relationships that they found for the two regions is difference in the dynamic factors leading to convection. In Florida, the low level convergence associated with the sea breeze circulation over the peninsula is important in triggering convective rains. Thunderstorms regularly develop in the afternoon in response to this diurnal circulation and convective systems are characterized by relatively little movement from the time the first clouds form to the dissipation of the system. In contrast, convective systems and thunderstorms in the Midwest are often initiated by a combination of migratory surface and upper-air dynamic factors. These midlatitude convective systems frequently form large clusters or lines which advect at 30 to 50 km hr^{-1}, and rarely develop, mature, and dissipate in the same general locale. Development is characterized by concurrent growth and dissipation as the system advects across a rather large region. Thus, the typical developmental sequence of convective systems in Florida and in Illinois are different, and this could play an important role in the lead time which can be anticipated between a signature in the surface divergence and the initiation of rain in the same location.

Since dynamic triggers for convection in Illinois may come from the middle and lower troposphere and be enhanced by local cloud circulations, the planetary boundary layer flow may respond more strongly and earlier than the surface flow. Thus both layers have been considered in this study.

The degree of correlation between kinematic parameters and rainfall parameters was determined in an attempt to quantize the relationships, if any. Surface and sub-cloud parameters were treated separately, with the former confined to measures of divergence. For the sub-cloud layer, vorticity and vertical motion were also considered. The rainfall variables were 1) total rainfall in triangle, 2) maximum 30-minute point accumulation in the triangle, 3) total rainfall in triangle plus that in the "downstorm" area, and 4) maximum 30-minute point accumulation for the area defined by the triangle and the "downstorm" region. (The downstorm region was defined as the area added when the sides of the triangle were "translated" a distance equal to that traveled by the storms in one hour. Total rainfall was the total accumulation for all raingages in applicable region.)

In all 12 storm events occurred in the pibal triangle during the eight days with rain. For this "statistical" analysis of sub-cloud paramters the sample was reduced to seven storms. Some cases had to be omitted because kinematic parameters could not be calculated for pertinent times due to rain or other obscurations at a pibal site. Also on several occasions, it was evident that the wind fields were affected by convective systems outside of the triangle, and that the resulting measurements represented a composite of effects. Thus the final sample of seven relates to convective rains originating in or close to the triangle.

The correlation coefficients between rain and sub-cloud parameters in this seven storm sample were all 0.8 or greater

(Table 1). The column average divergence at, or just prior to, the initiation of rain within the triangle was storngly correlated with rain, with coefficients of -0.82 or -0.83 for all rain categories, (i.e., positive correlations of rain with convergence). Similarly, the correlations coefficients between rain and the minimum values of divergence within 2 hours of the start of rain ranged from -0.85 to -0.87. The correlation between rain and vertical velocity at 700 m MSL, an integration of divergence from the surface to 700 m MSL, was similarly high. The column average vorticity at the measurement time closest to the initiation of rain in the triangle and the maximum cyclonic vorticity within 2 hours of the start of rain were equally well correlated to rainfall, with correlation coefficients of 0.80 to 0.97. The maximum values of cyclonic vorticity were observed within 30 minutes of the initiation of rain in 5 of the 7 cases.

On some of the days (14, 24, and 30 July) convergence maxima were observed as much as 3 to 4 hours prior to the initiation of rain. However, the relative vorticity at the same time was either very weakly cyclonic or anticyclonic. The rains did not start until the sub-cloud vorticity was cyclonic, except for the storm on 23 August. On this day cyclonic vorticity and convergence was observed in the sub-cloud layer prior to rain within the triangle but the vorticity changed to weakly anticyclonic when the rain started. The wind fields were evidently being affected by the low-level outflow from the thunderstorms.

The correlation coefficients between surface divergence and rainfall are shown in Table 2, for both the limited sample used for the sub-cloud layer calculations and for the sample which included cases where pibal measurements were missing. Surface divergence at the time closest to start of rain in the triangle was the more closely correlated to the rain than the other surface parameters which were tested. The correlation coefficients ranged from -0.52 to -0.60, not as high as those for sub-cloud divergence and rain. The other divergence variables, including the change associated with the "gust front signature", had correlation coefficients of less than 0.50.

The small sample size does not permit us to attach much statistical significance to the correlations. Nevertheless, there is an indication that the sub-cloud parameters examined could explain more of the variance in rainfall than the best surface divergence parameter. There appears to be a strong positive relationship between rainfall and the strength of the sub-cloud inflow prior to the start of rain, and between rainfall and positive relative vorticity. The stronger correlation of rain to the sub-cloud layer should not be too surprising since the cloud "feeds" on the whole layer and the measurements in this region should provide a better indicator of the integrated mass flow into the cloud. The surface values only represent a portion of the inflow from the surface to cloud base.

Watson and Holle (1982) using a larger sample from the VIN network also found that correlations between surface divergence

Table 1. Correlation coefficient between rainfall in and downstorm of pibal triangle and sub-cloud kinematic parameters. Sample size shown in parentheses. See text for explanations.

	Rainfall Total		30 Minute Maximum	
	Triangle	Triangle + Downstorm	Triangle	Triangle + Downstorm
Divergence[1] preceding rain by <30 min	-.83 (7)	-.82 (7)	-.83 (7)	-.83 (7)
Minimum Divergence within 2 hours prior to start of rain in triangle	-.87 (7)	-.86 (7)	-.87 (7)	-.85 (7)
Vertical Velocity[2] preceding rain <30 min	.85 (7)	.84 (7)	.85 (7)	.84 (7)
Maximum Vertical Velocity[2] within 2 hours of start of rain in triangle	.82 (7)	.81 (7)	.83 (7)	.81 (7)
Vorticity[1] preceding rain by <30 min	.89 (7)	.84 (7)	.88 (7)	.80 (7)
Maximum Cyclonic Vorticity within 2 hours prior to start of rain in triangle	.97 (7)	.97 (7)	.96 (7)	.95 (7)

(1) Column-average divergence and vorticity used in calculating correlation

(2) Vertical velocity at 700 m MSL, calculated by integrating continuity equation upward from surface

Table 2. Correlation coefficient between rainfall and surface divergence parameters. Sample size shown in parentheses.

	Total		30 Minute Maximum	
	Triangle	All Areas	Triangle	All Areas
Surface Divergence	-0.52 (9)	-0.53 (8)	-0.60 (9)	-0.53 (8)
start of rain	-0.51 (7)	-0.54 (7)	-0.50 (7)	-0.54 (7)
Surface Divergence	-0.04 (9)	0.46 (8)	-0.11 (9)	0.49 (8)
30 minutes prior to rain	0.14 (7)	0.12 (7)	0.21 (7)	0.16 (7)
Surface Convergence	0.06 (8)	0.34 (7)	-0.11 (8)	-0.34 (7)
change associated gust front	-0.45 (6)	-0.45 (6)	-0.47 (6)	-0.48 (6)
Divergence change 60	-0.36 (9)	-0.28 (8)	-0.37 (9)	-0.18 (8)
minutes prior to start of rain	-0.39 (7)	-0.37 (7)	-0.40 (7)	-0.38 (7)

and rain were low in Illinois, but improved when the data were stratified by the wind speed in the lowest 3 km. The correlation coefficient was higher when the winds were less than 5 m s^{-1}, and lower when they were stronger (-.73 and -.46, respectively for the average of the divergence at uniformly space grid points). However, a significant fraction of the rain events were <u>not</u> detected in the divergence time series as a "convergence event" (defined by them as sustained change in divergence of less than -2.5×10^{-5} sec^{-1} for more than 10 minutes). Nine rains out of 22 were undetected for low winds and 19 out of 50 for winds >5 m s^{-1}.

The relationships between rainfall and sub-cloud layer kinematic parameters was sufficiently good to suggest that they may provide statistical predictors of precipitation amount which could be useful in weather modification experiments. However because of the small sample size, the low correlation coefficients for rain and surface divergence, and short lead time, it is not possible to draw a favorable conclusion as to the value of sub-cloud and surface kinmatics as a now-casting tool for rainfall in the Midwest.

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